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NAVAL POSTGRADUATE SCHOOL

Monterey, California



THESIS

A COMPARATIVE STUDY ON THE REALIZABILITY
OF BIQUADRATIC FUNCTIONS

by

Achmad Ischak Suparman

June 1976

Thesis Advisor:

Shu-gar Chan

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A Comparative Study on the Realizability
of Biquadratic Functions

by

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MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

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June 1976

ABSTRACT

A comparative study is made on the realizability conditions of various special cases as well as the general case of the positive-real biquadratic functions. Computer programs are written for this study to illustrate the realizability regions of zeros (or poles) of the functions. A limited study is also made on the sensitivity of the function to variation of element value in a realization.

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I. INTRODUCTION

The problem of realizability of biquadratic functions as driving point immittance has been studied by a number of investigators [1] - [11], with realizability conditions given for various special cases as well as for the general case of biquadratic functions. It has been proved [10] that, given a pair of poles, the location of the zeros are limited by two curves, one of which is the locus of the zeros such that the biquadratic function is a minimum positive real function.

In Chapter II of this paper, various realizability conditions are reviewed and illustrated. FORTRAN programs are written in Chapter III for illustration as well as comparison of different cases.

Many forms of realizations of positive-real biquadratic functions are well known. Some of these forms are utilized, in Chapter IV, to study the sensitivity problem related to the realizability of the function. The method of graphical representation by Chan [13] is applied in this study. A computer program is written for the illustration of the variation of sensitivity phasors [13] as functions of element values.

Finally, in Chapter V, a discussion on the results is made together with some suggestions for further studies.

II. REALIZABILITY CONDITIONS

A. INTRODUCTION

Consider a general biquadratic function

$$Z(s) = \frac{s^2 + 2\sigma_z s + \omega_z^2}{s^2 + 2\sigma_p s + \omega_p^2} = \frac{(s + z')(s + z'')}{(s + p')(s + p'')} \quad (1)$$

or

$$Z(j\omega) = \frac{-\omega_z^2 + 2\sigma_z j\omega + \omega_z^2}{-\omega_p^2 + 2\sigma_p j\omega + \omega_p^2} = \frac{(\omega_z^2 - \omega^2) + j\omega 2\sigma_z}{(\omega_p^2 - \omega^2) + j\omega 2\sigma_p} \quad (2)$$

It has been investigated by Chan and Phung [10], that a biquadratic function $Z(s)$ as given in equation (1) with conjugate-complex zeros in the open half plane is realizable as a driving point immittance with passive one-port if and only if the zeros are located either on the curve C_0 or C_1 or inside the area delimited by curves C_0 and C_1 , whose polar equations are given respectively by

$$\max \omega_z = \omega_p + 2\sigma_p \cos \phi_z' + 2 \left[\sigma_p \cos \phi_z' (\sigma_p \cos \phi_z' + \omega_p) \right]^{\frac{1}{2}} \quad (3-a)$$

and

$$\min \omega_z = \omega_p + 2\sigma_p \cos \phi_z' - 2 \left[\sigma_p \cos \phi_z' (\sigma_p \cos \phi_z' + \omega_p) \right]^{\frac{1}{2}} \quad (3-b)$$

where ϕ_z' denotes the compliment of the argument of the zero z' , such

that

$$\sigma_z = \omega_z \cos \phi_z'.$$

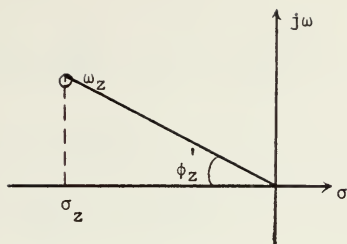


Figure 1

B. NECESSARY AND SUFFICIENT CONDITIONS

To obtain the real part of $Z(j\omega)$ of equation (2), multiply and divide this equation with the conjugate of the denominator, so that

$$\operatorname{Re} [Z(j\omega)] = \frac{(\omega_p^2 - \omega^2)(\omega_z^2 - \omega^2) + 4\sigma_p\sigma_z\omega^2}{(\omega_p^2 - \omega^2)^2 + 4\sigma_p^2\omega^2}. \quad (5)$$

$Z(s)$ is positive real if the numerator of expression (5) is nonnegative for all values of ω , that is

$$N(\omega^2) = \omega^4 - \omega^2(\omega_z^2 + \omega_p^2 - 4\sigma_z\sigma_p) + \omega_z^2\omega_p^2. \quad (6)$$

Now we have the following two conditions [10]:

Condition-1

$N(\omega^2)$ has complex or equal positive real roots.

Condition-2

$N(\omega^2)$ has nonpositive real roots.

Condition-1 implies the discriminant of $N(\omega^2)$ is negative or zero i.e.

$$D = (\omega_z^2 + \omega_p^2 - 4\sigma_z\sigma_p)^2 - 4\omega_z^2\omega_p^2 \leq 0 \quad (7)$$

or after factoring we get

$$\left[(\omega_z + \omega_p)^2 - 4\sigma_z \sigma_p \right] \left[(\omega_z - \omega_p)^2 - \sigma_z \sigma_p \right] \leq 0 ; \quad (7-a)$$

thus condition-1 is satisfied if

$$(\omega_z - \omega_p)^2 \leq 4\sigma_z \sigma_p < (\omega_z + \omega_p)^2 . \quad (7-b)$$

The right hand inequality is shown as strict since inequality corresponds to real roots which would in this case be nonpositive, which is a violation of condition-1.

Next, condition-2 implies the following two conditions simultaneously:

Condition-2a

$$D \geq 0 .$$

Condition-2b

$$\omega_z^2 + \omega_p^2 - 4\sigma_z \sigma_p \leq 0 .$$

It can be seen that both conditions 2a and 2b are satisfied if

$$4\sigma_z \sigma_p \geq (\omega_z + \omega_p)^2 . \quad (8)$$

With equations (7-b) and (8) we obtain the necessary condition for positive realness of $Z(s)$ to be

$$(\omega_z - \omega_p)^2 \leq 4\sigma_z \sigma_p . \quad (9)$$

Now suppose that equation (9) is satisfied with the equality sign. $Z(s)$ is then a minimum positive-real function since $N(\omega^2)$ has a double positive root ω_i , where

$$\omega_i^2 = \omega_z \omega_p . \quad (10)$$

Next suppose equation (9) is satisfied but not necessary as an equality, then

$$\sigma_z \geq \frac{(\omega_z - \omega_p)^2}{4\sigma_p} \quad (11)$$

The necessary and sufficient condition obtained in the above discussion can be conveniently and geometrically interpreted.

Suppose that the zeros z' and z'' are conjugate complex with negative real parts and the poles p' and p'' are similarly located in the open left half plane.

Let

$$\sigma_z = \omega_z \cos \phi_z' \quad (12-a)$$

where ϕ_z' denotes the compliment of the argument of the zero z' .

$$\text{If } \omega_z \geq \omega_p, \text{ then we let } \omega_z = \omega_p + u_0 \quad (12-b)$$

$$\text{If } \omega_z \leq \omega_p, \text{ then we let } \omega_z = \omega_p - u_1 \quad (12-c)$$

substituting equations (12-a) and (12-b) into equation (9), and after rearranging we get

$$u_0^2 - 4\sigma_p (\cos \phi_z') u_0 - 4\sigma_p \sigma_p \cos \phi_z' \leq 0 \quad (13-a)$$

and substituting equations (12-a) and (12-c) into equation (9) we get

$$u_1^2 + 4\sigma_p (\cos \phi_z') u_1 - 4\sigma_p \sigma_p \cos \phi_z' \leq 0 \quad (13-b)$$

Both polynomials in the left hand sides of the inequalities (13-a) and (13-b) have a positive real root and a negative real root, so that these

two conditions will be satisfied if u_0 and u_1 are nonnegative and smaller than or equal to the positive-real root of the left hand side polynomials in (13-a) and (13-b) respectively.

Thus solving for the positive real root and then substituting the result into equations (12-b) and (12-c) gives, for each value of $\phi_z' \leq 90^\circ$, the maximum and minimum values of ω_z , for which the necessary and sufficient condition for the positive realness of $Z(s)$ is satisfied.

Alternatively, we substitute equations (12-b) and (12-c) into equation (9) and get

$$u^2 - 4\sigma_z \sigma_p \leq 0$$

and

$$u_1^2 - 4\sigma_z \sigma_p \leq 0 .$$

Solving these two equations for the positive real root and substituting the results into the expression for ω_z , gives the maximum and minimum values of ω_z for which the positive realness of $z(s)$ is satisfied. Thus we have in this case the two equations

$$\max \omega_z = \omega_p + 2 \sqrt{\sigma_z \sigma_p} \quad (14-a)$$

and

$$\min \omega_z = \omega_p - 2 \sqrt{\sigma_z \sigma_p} . \quad (14-b)$$

Note that these equations will give the same results as equations (13-a) and (13-b) when poles of $Z(s)$ are complex, and will also give the realizable area of zeros of $Z(s)$ when the poles are real.

Thus given $Z(s)$ with complex conjugate poles in the left half plane, or with negative real poles, $Z(s)$ will be realizable if the zeros of $Z(s)$ are complex and lie on or within the curves of equations (14-a) and (14-b).

In the special case where $Z(s)$ has real poles and complex zeros, it has been shown that $z(s)$ can be realized by a five element series parallel circuit [11].

The key restriction in this case is given by

$$p'' (p'' - p') - (z' - p'')(z'' - p'') \geq 0 \quad (15)$$

where p' , p'' , z' and z'' are poles and zeros of

$$Z(s) = \frac{(s + z')(s + z'')}{(s + p')(s + p'')}$$

and $p'' > p'$.

If we substitute σ 's and ω 's for the p 's and z 's of (15), then we get

$$p' = -\sigma_p + \sqrt{\sigma_p^2 - \omega_p^2}$$

$$p'' = -\sigma_p - \sqrt{\sigma_p^2 - \omega_p^2}$$

$$z' = -\sigma_z + \sqrt{\sigma_z^2 - \omega_z^2}$$

$$z'' = -\sigma_z - \sqrt{\sigma_z^2 - \omega_z^2}$$

we also obtain

$$2\sigma_z \sigma_p + 2\sigma_z \sqrt{\sigma_p^2 - \omega_p^2} - \omega_z^2 - \omega_p^2 \geq 0$$

rearranging terms, we have

$$\omega_z^2 + \omega_p^2 \leq 2\sigma_z \sigma_p + 2\sigma_z \sqrt{\sigma_p^2 - \omega_p^2}.$$

Now since

$$\omega_z^2 + \omega_p^2 = (\omega_z - \omega_p)^2 + 2\omega_z \omega_p,$$

then we get

$$(\omega_z - \omega_p)^2 \geq 2\sigma_z \sigma_p + 2\sigma_z \sqrt{\sigma_p^2 - \omega_p^2} - 2\omega_z \omega_p.$$

Comparing this condition to that for the general case in equation (9), we obtain

$$2\sigma_z \sigma_p + 2\sigma_z \sqrt{\sigma_p^2 - \omega_p^2} < 4\sigma_z \sigma_p,$$

and since σ_z , σ_p , ω_z and ω_p are all positive numbers, the result becomes

$$(\omega_z - \omega_p)^2 \leq 2\sigma_z \sigma_p + 2\sigma_z \sqrt{\sigma_p^2 - \omega_p^2} - 2\omega_z \omega_p < 4\sigma_z \sigma_p$$

so that this is indeed more restrictive than the general case and we should not be surprised to find the area of realizability for this case enclosed by that of the general case.

In fact this argument could be used as a proof of the realizability of $Z(s)$ given in (15), since the area of this case is always enclosed by that of the general case as shown above.

The construction of the realizability region in this case will be in accordance with reference [11], that is

$$p'' M = r = p''^{\frac{1}{2}} (p'' - p')^{\frac{1}{2}},$$

where $p'' > p'$.

C. SAMPLE ILLUSTRATIONS

(a) Complex poles ($\omega_p > \sigma_p$)

Let $\sigma_p = 3$

and $\omega_p = 5$.

Then from equations (14-a) and (14-b) we get

$$\begin{aligned}\omega_z \text{ max} &= \omega_p + 2\sqrt{\sigma_z \sigma_p} \\ &= 5 + 2\sqrt{3\sigma_z} = 5 + \sqrt{12\sigma_z},\end{aligned}$$

and

$$\begin{aligned}\omega_z \text{ min} &= \omega_p - 2\sqrt{\sigma_z \sigma_p} \\ &= 5 - \sqrt{12\sigma_z}.\end{aligned}$$

We obtain the limitation of σ_z as follows:

$$\sigma_z < \omega_z \text{ for complex zeros.}$$

If we let $\omega_z \text{ max} = \sigma_z$, then we get

$$\begin{aligned}\omega_z &= 5 + \sqrt{12\sigma_z} \\ &= 20.8 = \sigma_z, \text{ maximum value for } \sigma_z, \text{ for } \omega_z \text{ max.}\end{aligned}$$

Similarly if $\omega_z \text{ min} = \sigma_z$, then

$$\omega_z = 1.2 = \sigma_z, \text{ maximum value for } \sigma_z, \text{ for } \omega_z \text{ min.}$$

(b) Real Poles

Let $\sigma_p = 2.5$ and

$$\omega_p = 2 \quad \text{with poles at } (-1, -4).$$

Then we obtain

$$\begin{aligned}\omega_z \text{ max} &= \omega_p + 2\sqrt{\sigma_z \sigma_p} \\ &= 2 + \sqrt{10\sigma_z}\end{aligned}$$

and

$$\omega_z \text{ min} = \omega_p - \sqrt{10\sigma_z} \text{ .}$$

If $\omega_z \text{ max} = \sigma_z$, then

$$\omega_z = 2 + \sqrt{10\sigma_z}$$

$$= 13.7 = \sigma_z, \text{ max } \sigma_z \text{ for } \omega_z \text{ max and complex zeros.}$$

From the examples given in this section it can be seen that the realizability region of a biquadratic function is dependent upon the restriction we place on the function. That is, as we place more restrictions on the function and proceed from a general function with complex poles to one with real poles which is realizable by certain technique, we see that at each step the realizability region decreases. This decrease of freedom from the additional restriction is to be expected.

III. COMPUTER STUDY ON REALIZABILITY

For a given location of the complex pole pair (σ_p and ω_p specified) in the open left half plane, C_0 and C_1 are simply plots of ω_z versus ϕ_z' . Thus the computer program was written to accept σ_p and ω_p as inputs and to generate C_0 and C_1 on either the line printer or the Calcomp plotter. Some sample outputs are shown in Figure A-1.A and A-1.B in Appendix A.

The curves are for a normlized set of pole locations with

$$\omega_p = 1$$

and

$$0^\circ < \phi_p' < 90^\circ,$$

where ϕ_p' is the compliment of the argument of the pole p .

Varying ϕ_p' from 0° to 90° corresponds to shifting the poles along a circular path from the negative real axis to the $j\omega$ axis.

The program was then modified to produce a set of curves C_0 and C_1 for various pole locations. Given a specific pair of poles, two types of plots may be obtained, depending upon the requirements of the problem.

If an accurate plot of the realizability region is required, the program can be used so that a plot of the realizability region is required, the program can be used so that a plot similar to that shown in Figure A-1.A is obtained. Otherwise if a quick estimate is all that is desired, a plot similar to the one in Figure A-1.B can be used.

Other outputs were obtained for various pole locations.

Results obtained for the following cases are included, with program listing, in Appendix A and B respectively:

1. Complex poles with σ_p moves toward a constant ω_p .

2. Complex poles with ω_p moves toward a constant σ_p .
3. Complex poles that are moving toward the origin.
4. Real negative poles with one of which moving toward the origin while the other remains stationary.
5. Real negative poles with one of which moving toward infinity while the other remains stationary.
6. Double real poles moving from the neighborhood of the origin toward infinity.
7. Pure imaginary poles moving toward the origin.
8. Pure imaginary poles moving away from the origin.

The above cases are now described in the following sections. In each case a figure is included showing the pole locations with their values shown in the accompanying table, in which the location of the corresponding computer output plots are indicated.

Case 1

This case illustrates the zeros region for given complex poles with

σ_p moves toward a constant ω_p .

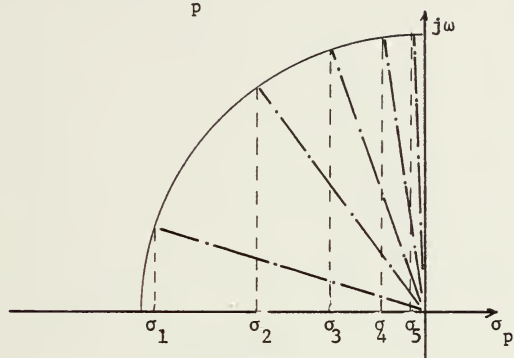


Figure 2.

Five different poles (conjugate poles are not shown) are given in accordance to show the zero regions for each σ_p as ω_p remains constant. The locations of each pole are tabulated in Table 1.

Table 1

| Pole | σ_p | ω_p | Computer Plot |
|-------|------------|------------|----------------|
| C_1 | 0.999 | 1.0 | Figure A-1.A,B |
| C_2 | 0.707 | 1.0 | Figure A-2 |
| C_3 | 0.55 | 1.0 | Figure A-3 |
| C_4 | 0.25 | 1.0 | Figure A-4 |
| C_5 | 0.1 | 1.0 | Figure A-5 |

Case 2

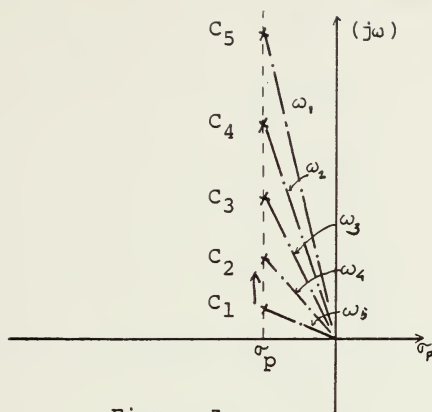


Figure 3.

This case illustrates the zeros region for given complex poles with

ω_p moves toward a constant σ_p .

Five different pole locations are shown in Table 2.

Table 2

| Pole | σ_p | ω_p | Computer Plot |
|-------|------------|------------|------------------------------------|
| C_1 | 1.0 | 1.05 | All plots are shown in figure A-7. |
| C_2 | 1.0 | 2.0 | |
| C_3 | 1.0 | 3.0 | |
| C_4 | 1.0 | 5.0 | |
| C_5 | 1.0 | 8.0 | |

Case 3

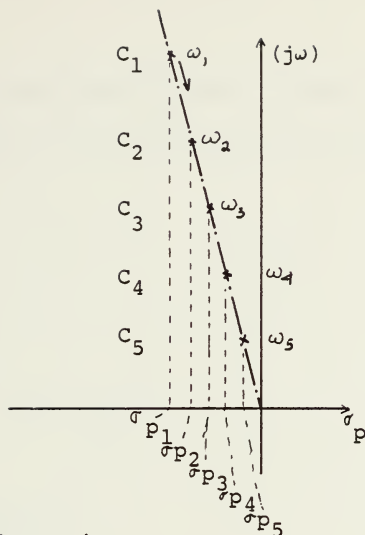


Figure 4.

This case illustrates the zeros region for given complex poles that are moving toward the origin. Five different pole locations are shown in Table 3.

Table 3

| Pole | σ_p | ω_p | Computer Plot |
|-------|------------|------------|------------------------------------|
| C_1 | 4.0 | 30.652 | All plots are shown in Figure A-8. |
| C_2 | 2.0 | 15.326 | |
| C_3 | 0.5 | 3.834 | |
| C_4 | 0.1 | 0.766 | |
| C_5 | 0.01 | 0.077 | |

Case 4

This case illustrates the zeros region for given real negative poles with one of which moving toward the origin while the other remains stationary.

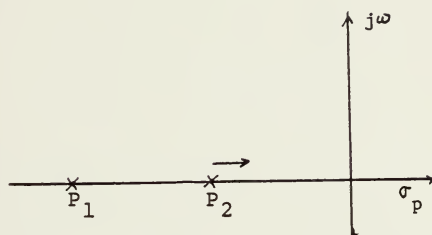


Figure 5.

Five different pole locations are shown in Table 4.

Table 4

| Condition | Pole P_1 | Pole P_2 | σ_p | ω_p |
|-----------|------------|------------|------------|------------|
| C_1 | 8.0, 0 | 4.0, 0 | 6.0 | 5.657 |
| C_2 | 8.0, 0 | 1.0, 0 | 4.5 | 2.828 |
| C_3 | 8.0, 0 | 0.5, 0 | 4.25 | 2.0 |
| C_4 | 8.0, 0 | 0.1, 0 | 4.05 | 1.414 |
| C_5 | 8.0, 0 | 0.05, 0 | 4.025 | 0.632 |

All plots are shown in computer output Figure A-9.

Case 5

This case illustrates the zeros region for given real negative poles with one of which moving toward infinity while the other remains stationary.

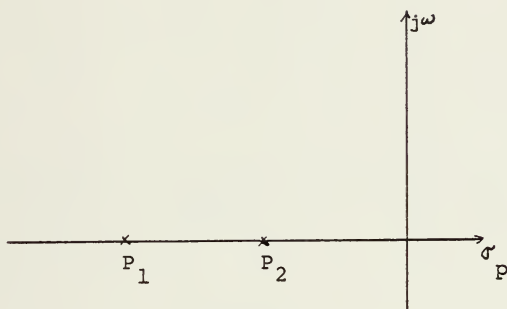


Figure 6.

Five different pole locations are shown in Table 5.

Table 5

| Condition | Pole P_1 | Pole P_2 | σ_p | ω_p |
|-----------|------------|------------|------------|------------|
| C_1 | 8.0,0 | 2.0, 0 | 5.0 | 4.0 |
| C_2 | 15.0,0 | 2.0, 0 | 8.5 | 5.477 |
| C_3 | 30.0,0 | 2.0, 0 | 16.0 | 7.746 |
| C_4 | 50.0,0 | 2.0, 0 | 26.0 | 10.0 |
| C_5 | 100.0,0 | 2.0, 0 | 56.0 | 14.142 |

All plots are shown in computer output Figure A-10.

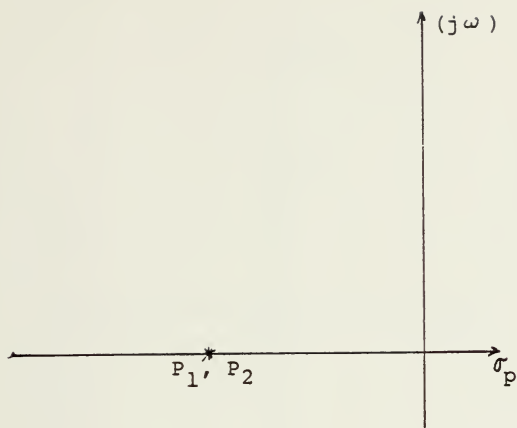
Case 6

Figure 7.

This case illustrates the zeros region for given double real poles moving from the neighbourhood of the origin toward infinity. Five different pole locations are shown in Table 6.

Table 6

| Condition | Pole $P_1=P_2$ | ζ_p | ω_p | Computer Plot |
|-----------|----------------|-----------|------------|--|
| C_1 | 1.0, 0 | 1.0 | 1.0 | All plots are shown in computer output |
| C_2 | 2.0, 0 | 2.0 | 22.0 | |
| C_3 | 5.0, 0 | 5.0 | 5.0 | |
| C_4 | 10.0, 0 | 10.0 | 10.0 | |
| C_5 | 25.0, 0 | 25.0 | 25.0 | |

Case 7

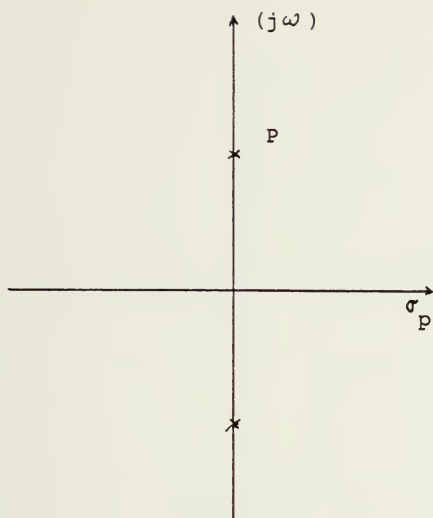


Figure 8.

This case illustrates the zeros region for given pure imaginary poles moving toward the origin. Five different pole locations are shown in Table 7.

Table 7

| Condition | σ_p | ω_p | Computer Plot |
|-----------|------------|------------|-------------------------------------|
| C_1 | 0.0 | 3.0 | All plots are shown in Figure A-12. |
| C_2 | 0.0 | 1.0 | |
| C_3 | 0.0 | 0.5 | |
| C_4 | 0.0 | 0.1 | |
| C_5 | 0.0 | 0.05 | |

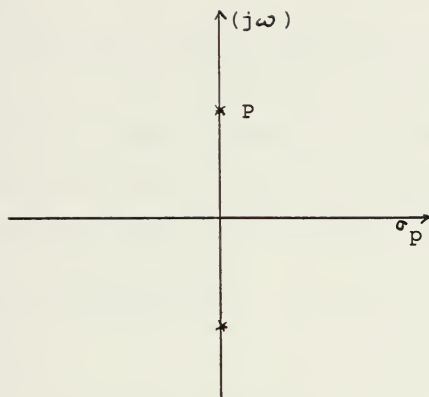
Case 8

Figure 9.

This case illustrates the zeros region for given pure imaginary poles moving away from the origin. Five different pole locations are shown in Table 8.

Table 8

| Condition | σ_p | ω_p | Computer Plot |
|-----------|------------|------------|---|
| C_1 | 0.0 | 4.0 | All plots are shown in computer output Figure A-13. |
| C_2 | 0.0 | 10.0 | |
| C_3 | 0.0 | 20.0 | |
| C_4 | 0.0 | 100.0 | |
| C_5 | 0.0 | 200.0 | |

IV. SENSITIVITY STUDY

A. INTRODUCTION

It has been shown [12], that in a linear and not necessarily reciprocal network, with only one independent source and initially at rest, the ratio of the Laplace transform of the current in any branch or of the voltage across any node pair to the Laplace transform of either an independent voltage or current source is given by

$$T(x) = \frac{W T_x(0) + x T_x(\infty)}{W + x} \quad (16)$$

where

x = an adjustable immittance.

$T(x)$ = the network function relating a response to an excitation.

$T_x(0) = \lim_{x \rightarrow 0} T(x)$ = the network function evaluated with $x = 0$, $T_x(0)$ is assumed to be finite.

$T_x(\infty) = \lim_{x \rightarrow \infty} T(x)$ = the network function evaluated when $x = \infty$, $T_x(\infty)$ is assumed to be finite.

W = the Thevenin immittance (independent of x) seen looking back into network from the terminals of the adjustable immittance. W is assumed to be finite.

Equation (16) is generic in form in that x can be either an impedance or admittance. In this paper the symbol $T(x)$ is used to denote a driving point immittance.

B. GRAPHICAL REPRESENTATION OF $T(x)$

Consider equation (16) for the case of a driving point immittance function as shown in Figure 10.

Dividing numerator and denominator of equation (16) by W , we get

$$T(x) = \frac{T_x(0) + \frac{x}{W} T_x(\infty)}{1 + \frac{x}{W}}$$

which can be rewritten as,

$$T(x) = \frac{T_x(\infty) \left(1 + \frac{x}{W}\right) + T_x(0) - T_x(\infty)}{1 + \frac{x}{W}}$$

or

$$T(x) = T_x(\infty) + \frac{T_x(0) - T_x(\infty)}{1 + \frac{x}{W}} \quad (17)$$

Let

$$T(x) = T_x(\infty) + V \quad (18)$$

where

$$V = \frac{T_x(0) - T_x(\infty)}{1 + \frac{x}{W}} \quad (19)$$

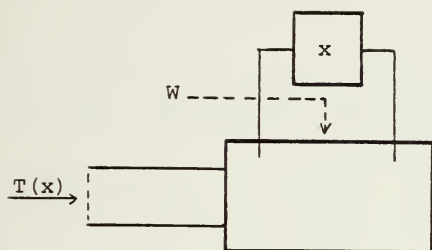


Figure 10.

Driving point immittance with variable component x .

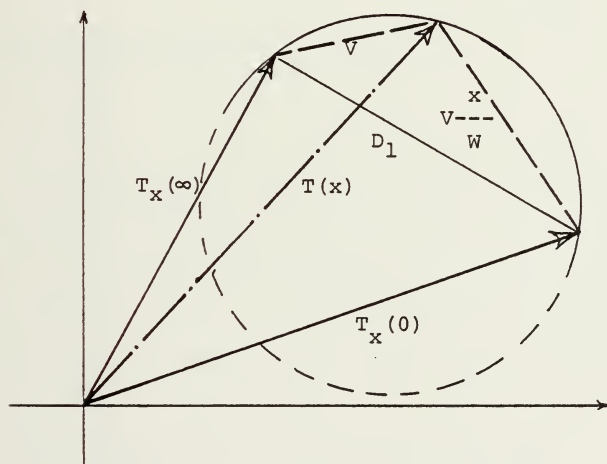


Figure 11.

Graphical representation of $T(x)$ phasor.

From equation (19) we have

$$V + V \frac{x}{W} = T_x(0) - T_x(\infty) \quad (20)$$

we note that $T_x(0)$ and $T_x(\infty)$ are fixed quantities.

Now treat each quantity in (20) as phasor, i.e.

$$V = |V| \exp. j\theta_1$$

and

$$W = |W| \exp. j\theta_2$$

then the left hand side of equation (20) represents the sum of two phasors.

If x is real, then the phasor

$$V \frac{x}{W} = x \left| \frac{V}{W} \right| \exp. j(\theta_1 - \theta_2)$$

is lagging behind the phasor V by an angle

$$\theta = \theta_1 - \theta_2.$$

Since $T_x(0)$ and $T_x(\infty)$ are two fixed quantities, the right hand side of equation (20) is constant so that the left hand side of (20) is constant. This requires that the angle must be constant (as x varies).

This implies that the tip of phasor V describes the arc of the circle, of which the quantity $T_x(0) - T_x(\infty)$ is a chord as shown in Figure 11.

To construct the circle we proceed as follows [13]:

1. Plot $T_x(\infty)$ and $T_x(0)$ as two phasors from the origin.
2. Draw a straight line D_1 through the tips of the two phasors in step 1.

3. Calculate the angle and draw a straight line D_2 from the tip of $T_x(0)$ forming angle with D_1 having the value $-\theta$ measuring clockwise from D_1 .

Therefore D_2 is tangent to the circular locus of T_x .

The centre of this circle, O' , is located at the intersection of the two perpendicular lines erected on the chord in the middle of $T_x(0) - T_x(\infty)$ and D_1 at the tip of $T_x(0)$, as shown in Figure 12.

Knowing the locus of $T(x)$ as x varies from zero to infinity, we can graphically determine $T(x)$ at any value of x .

C. GRAPHICAL REPRESENTATION OF SENSITIVITY PHASOR

If we define the sensitivity as

$$S_x^{T(x)} = \frac{d T(x)}{dx}$$

then with equation (16) we can obtain, [13]

$$S_x^{T(x)} = \frac{T_x(0) - T_x(\infty)}{W \left[1 + \frac{x}{W} \right]^2}$$

or

$$\frac{x S_x^{T(x)}}{V \frac{x}{W}} = - \frac{V}{T_x(0) - T_x(\infty)}$$

where

$$V = \frac{T_x(0) - T_x(\infty)}{1 + \frac{x}{W}}.$$

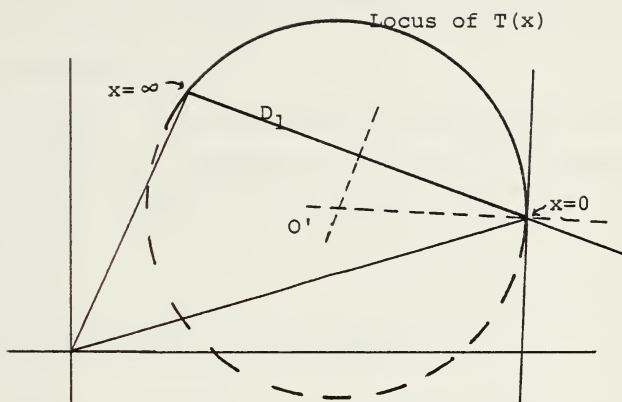


Figure 12.

Graphical representation of locus of $T(x)$.

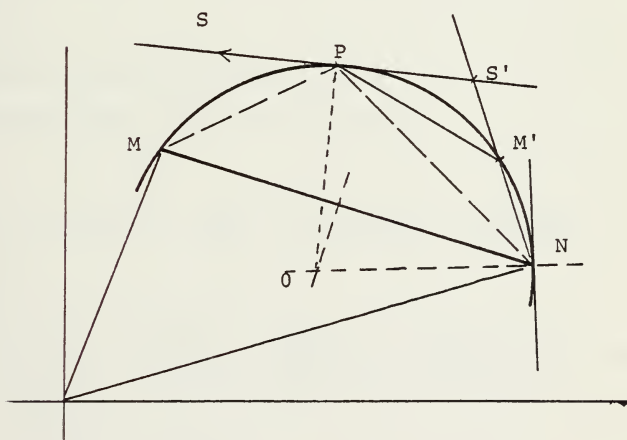


Figure 13.

Graphical representation of sensitivity phasor S .

It can be shown [13] that the sensitivity of a function may be graphically represented by a phasor such as \overline{PS} as shown in Figure 13.

D. SAMPLE ILLUSTRATION

As an illustration of the above discussion in this chapter, let us consider a biquadratic p.r. function as an RC driving point admittance, which can be realized in Foster 2 form as shown in Figure 14.

Let

$$Y(s) = \frac{s^2 + 4s + 3}{s^2 + 6s + 8} = \frac{(s+1)(s+3)}{(s+2)(s+4)}$$

which can be realized in Foster 2 form with the element value as given in Figure 5, in which all resistance and capacitances are measured in Ohms and Farads respectively.

Now let R_2 change by the amount ΔR , such that

$$0 < \Delta R < \infty .$$

Thus, Figure 15 is modified as shown in Figure 16.

We can calculate $T_x(0)$, $T_x(\infty)$ and W as follows:

$$\begin{aligned} T_x(0) &= Y(s, \Delta R=0) = \frac{1}{R_0} + \frac{1}{R_1 + 1/sC_1} + \frac{1}{R_2 + 1/sC_2} \\ &= .375 + \frac{.125 s}{.5 s + 1} + \frac{.09375 s}{.25 s + 1} = \frac{s^2 + 4s + 3}{s^2 + 6s + 8} . \quad (24) \end{aligned}$$

$$\begin{aligned} T_x(\infty) &= Y(s, \Delta R=\infty) = \frac{1}{R_0} + \frac{1}{R_1 + 1/sC_1} \\ &= .375 + \frac{.125 s}{.5 s + 1} = \frac{2.5 s + 3}{4 s + 8} . \quad (25) \end{aligned}$$

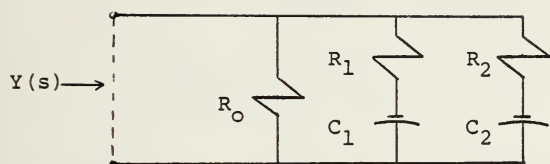


Figure 14.

The realization of Foster-2 form of driving point admittance $Y(s)$.

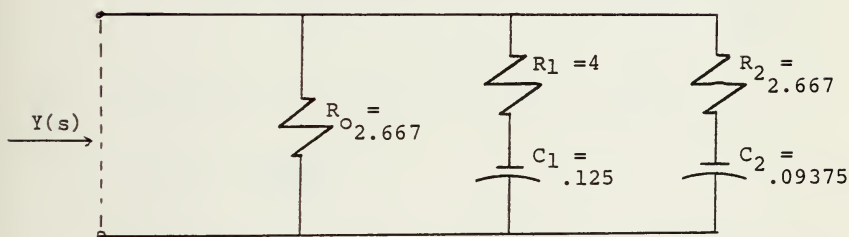


Figure 15.

The realization of biquadratic p.r. driving point admittance in Foster 2 form, where

$$Y(s) = \frac{s^2 + 4s + 3}{s^2 + 6s + 8}.$$

$$\begin{aligned}
W &= R_2 + \frac{1}{sC_2} + \frac{1}{Y(s, \Delta R=\infty)} \\
&= 2.667 + \frac{10.667}{2} + \frac{4s+8}{2.5s+3} \\
&= \frac{14.5s^2 + 40s + 99}{7.5s^2 + 9s} \quad . \quad (26)
\end{aligned}$$

From expression (26) we obtain the expression $\frac{x}{W}$ to be

$$\frac{x}{W} = \frac{7.5s^2x + 9sx}{14.5s^2 + 40s + 99} \quad . \quad (27)$$

Substitute equations (24), (25), (26) and (27) into equation (22) we get,

$${}_sT_x(x) = - \frac{\frac{s^2 + 4s + 3}{s^2 + 6s + 8} - \frac{2.5s + 3}{4s + 8}}{\frac{14.5s^2 + 40s + 99}{7.5s^2 + 9s} \left[1 + \frac{7.5xs^2 + 9xs}{14.5s^2 + 40s + 99} \right]^2} \quad , \quad (28)$$

then for simplification we write equation (28) above as,

$${}_sT_x(x) = - \frac{N(s,x)}{D(s,x)} \quad (29)$$

where $N(s,x)$ and $D(s,x)$ represent the numerator and denominator of the equation (28) respectively.

In the frequency domain, the expression in equation (29) can be written as,

$${}_sT_x(j\omega, x) = - \frac{N(j\omega, x)}{D(j\omega, x)} \quad (30)$$

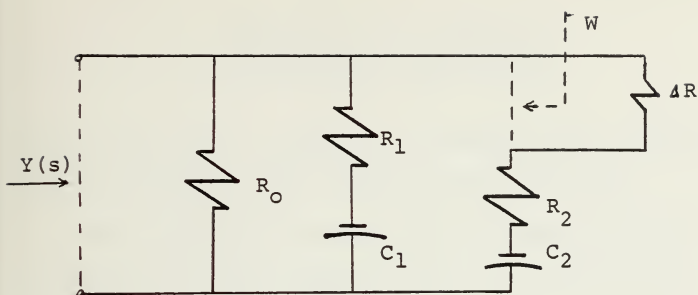


Figure 16.

Driving point admittance $Y(s)$ with variable resistance ΔR .

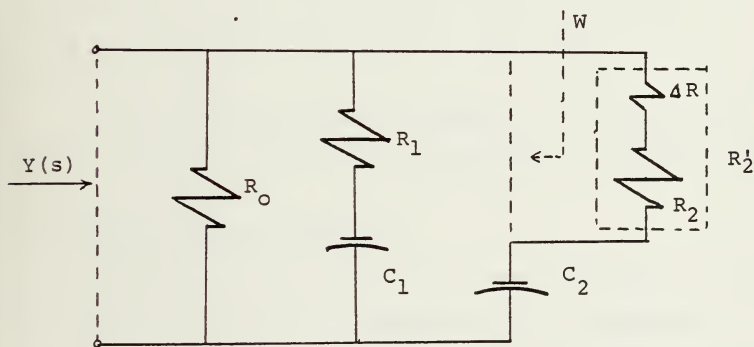


Figure 17.

Driving point admittance $Y(s)$ with variable resistance $R_2' = R_2 + \Delta R$.

$$= - \frac{\operatorname{Re} [N(j\omega, x)] + j \operatorname{Im} [N(j\omega, x)]}{\operatorname{Re} [D(j\omega, x)] + j \operatorname{Im} [D(j\omega, x)]} \quad (30a)$$

where $\operatorname{Re} [N(j\omega, x)]$, $\operatorname{Re} [D(j\omega, x)]$, $\operatorname{Im} [N(j\omega, x)]$ and $\operatorname{Im} [D(j\omega, x)]$ are real and imaginary parts of equation (30) respectively.

From equation (30a) we can obtain the magnitude of that sensitivity function. If we write equation (30a) in exponential form we have

$$S_x^{T(x)}(j\omega, x) = |S_x^{T(x)}| \exp(\phi_N - \phi_D) \quad (31)$$

where

$$S_x^{T(x)} = \text{magnitude of equation (30a)}$$

$$= \left[\frac{\{\operatorname{Re} [N(j\omega, x)]\}^2 + \{\operatorname{Im} [N(j\omega, x)]\}^2}{\{\operatorname{Re} [D(j\omega, x)]\}^2 + \{\operatorname{Im} [D(j\omega, x)]\}^2} \right]^{\frac{1}{2}}.$$

ϕ_N = the argument of the numerator of equation (30a).

ϕ_D = the argument of the denominator of equation (30a).

E. COMPUTER STUDY ON SENSITIVITY

In this section, the sensitivity of the function $T(x)$ with respect to the variation of one of its components will be investigated by computer. Consider the general expression $Y(x)$ in equation (16), which is repeated here for convenience.

$$T(x) = \frac{W T_x(s, x=0) + x T_x(s, x=\infty)}{W + s} \quad (16)$$

The sensitivity function of this equation is

$$S_x^{T(x)} = - \frac{T_x(s, x=0) - T_x(s, x=\infty)}{W \left[1 + \frac{x}{W} \right]^2} \quad (22)$$

As an example let us consider the function $Y(s)$, as we derived in section C,

$$Y(s) = \frac{(s+1)(s+3)}{(s+2)(s+4)}$$

and the realization of this function in Foster-2 form is shown in Figure 17.

For our investigation, let R_2 change with the amount of ΔR in series with R_2 and let

$$R_2' = R_2 + \Delta R.$$

To obtain the sensitivity $S_{R_2}^{T(s, R_2')}$ in terms of frequency and R_2' , we use the same calculation from equation (30).

The computer output in Appendix B shows us the plot of the magnitude of sensitivity function (30) versus R_2' . For this purpose we use equation (31) as reference.

Various cases are investigated using computer, resulting in plots of the magnitude of equation (31) versus R_2' for different frequencies.

V. CONCLUSION

In this paper, a comparative study has been made on the realizability conditions of a general biquadratic function. The graphical method of Chan and Phung [10] was used for this study and computer programs are written for verifications. General observations can be made as follows:

1. The realizability for the zeros expands considerably as the poles move from the imaginary axis to the real axis. This results both from C_0 moving away from the origin and C_1 moving toward the origin.

2. The limits on C_0 and C_1 are found easily from equations (3a) and (3b). As σ_p approaches zero, corresponding to the poles moving toward the $j\omega$ axis, both C_0 and C_1 tend toward the circle $\omega_z = \omega_p$ for all ϕ_z' . As can be seen from Figure A-6, C_0 and C_1 separate very rapidly for small movements of the poles away from the $j\omega$ axis. We can conclude that when $\sigma_p = 0$ we require $\omega_z = \omega_p$ in order for $Z(s)$ to be realizable with complex zeros. This can also be seen easily from equation (9).

3. As σ_p approaches ω_p , corresponding to the poles moving toward the real axis, C_0 approaches a value of $-5.828\omega_p$ on the real axis, and C_1 similarly approaches a value of $-0.172\omega_p$, as we can see in Figure A-1.A.

A brief study was made on sensitivity functions [13], some computer results are obtained. However, due to time limitation, a complete investigation in sensitivity was not possible and is left as a suggested topic for further studies.

APPENDIX A
COMPUTER OUTPUT

A. ZERO'S REGION

The illustration of zeros regions will be shown in this appendix.

The computer outputs show us the regions for various given omega and sigma poles.

Various cases are explained as follows:

Figure A-1a and A-1b show the zeros regions for given sigma pole = 0.999 and omega pole = 1.0 using Calcomp and PLOTP in the computer program respectively.

All the following plots show us the computer outputs by using Calcom in the computer program.

Figure A-2, A-3, A-4 and A-5 show us the plots of zeros regions for given sigma poles equal to 0.707, 0.55, 0.25 and 0.1 respectively with the amount of omega pole equal to 1.0 each.

Figure A-6 shows all plots given in Figure A-1a, A-2, A-3, A-4 and A-5 in one computer output.

Figure A-7 shows the plots of zeros regions as pole moves at sigma pole constant.

Figure A-8 shows the zeros regions as pole moves to the origin.

Figure A-9 and A-10 show the plots of zeros regions as pole moves to the origin and to infinity respectively.

Figure A-11 shows the plot of zeros regions of a double real negative poles as both move along the negative axis.

Figure A-12 and A-13 show us the zeros region plots of a given pair of pure negative poles, as both move to the origin and to the infinity respectively.

B. SENSITIVITY FUNCTION

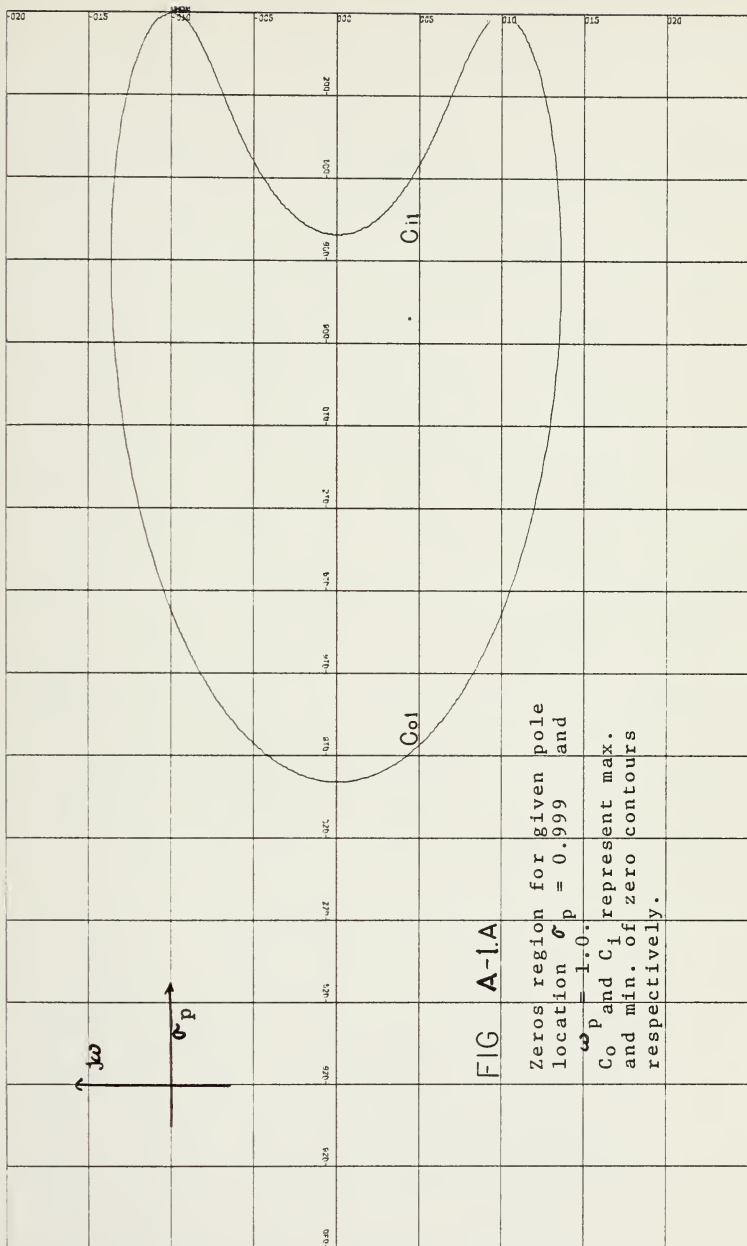
Various cases of sensitivity as a function of R'_2 are illustrated in the computer outputs for different particular frequencies.

The computer outputs show us the plots of sensitivity versus R'_2 and the tabulations of this plot.

The resistance R'_2 is select to be varied from the amount of 1 Ohm to 50 Ohms with increment to 1 Ohm. And the frequencies are choosen beginning at 1 rad/sec. up to 10,000 rad/sec.

Figure B-1, B-2, B-9 show us the sensitivity functions as R'_2 moves from 1 to 50 Ohms, at the frequencies of 1, 5, 10, 50, 100, 500, 1000, 5000 and 10000 rad/sec. The tabulations of those plots are also shown in Table B-1, B-2B-9 respectively.

Figure B-10 shows us five different plots of sensitivity functions illustrated in one computer output.



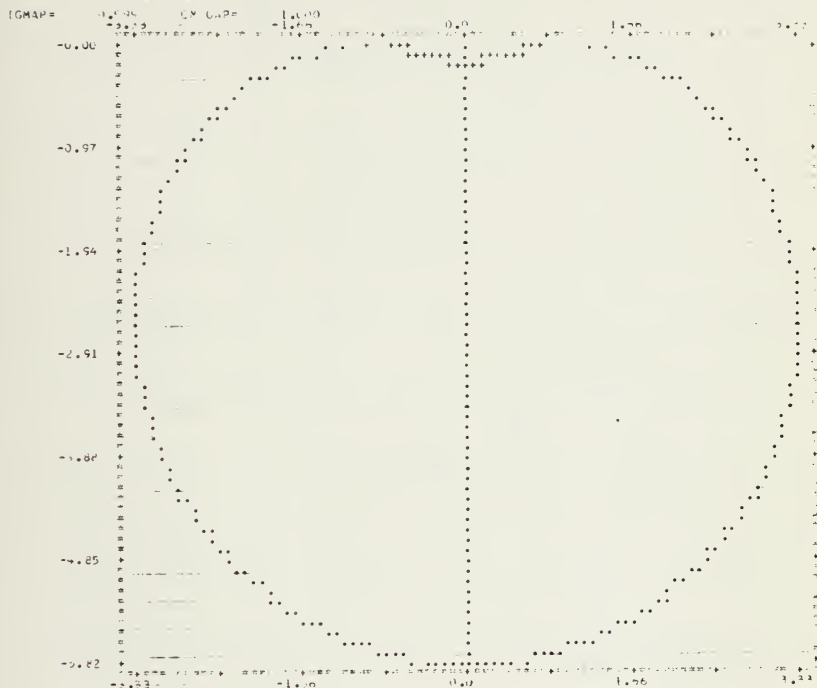
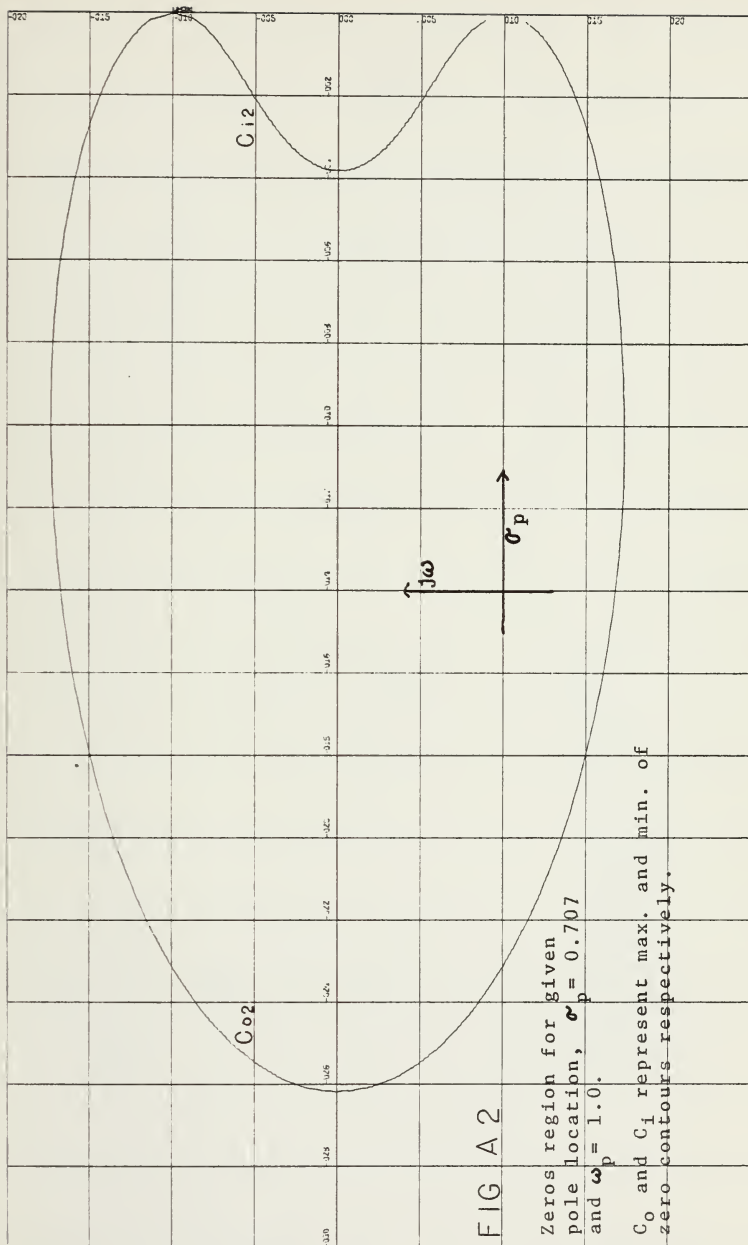
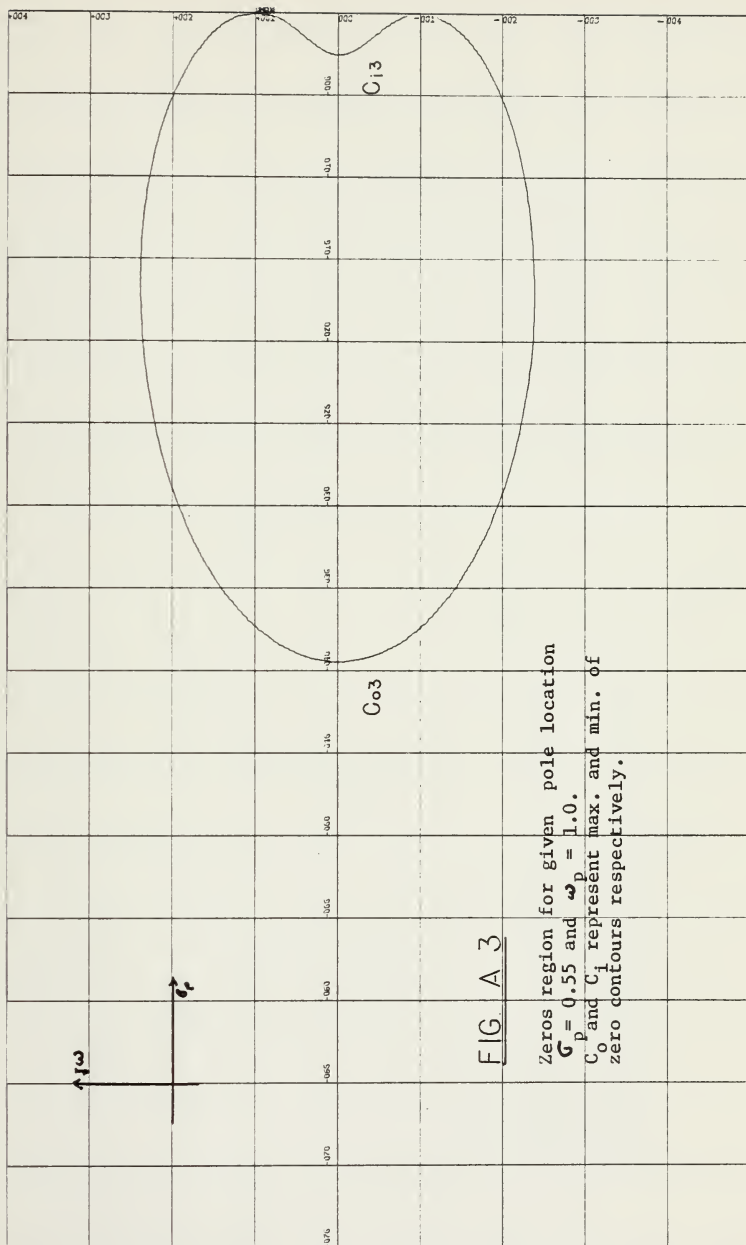


FIG. A-1B

This plot shows the Zero Region for given Sigma pole
 = 0.999 and Omega pole = 1.000.





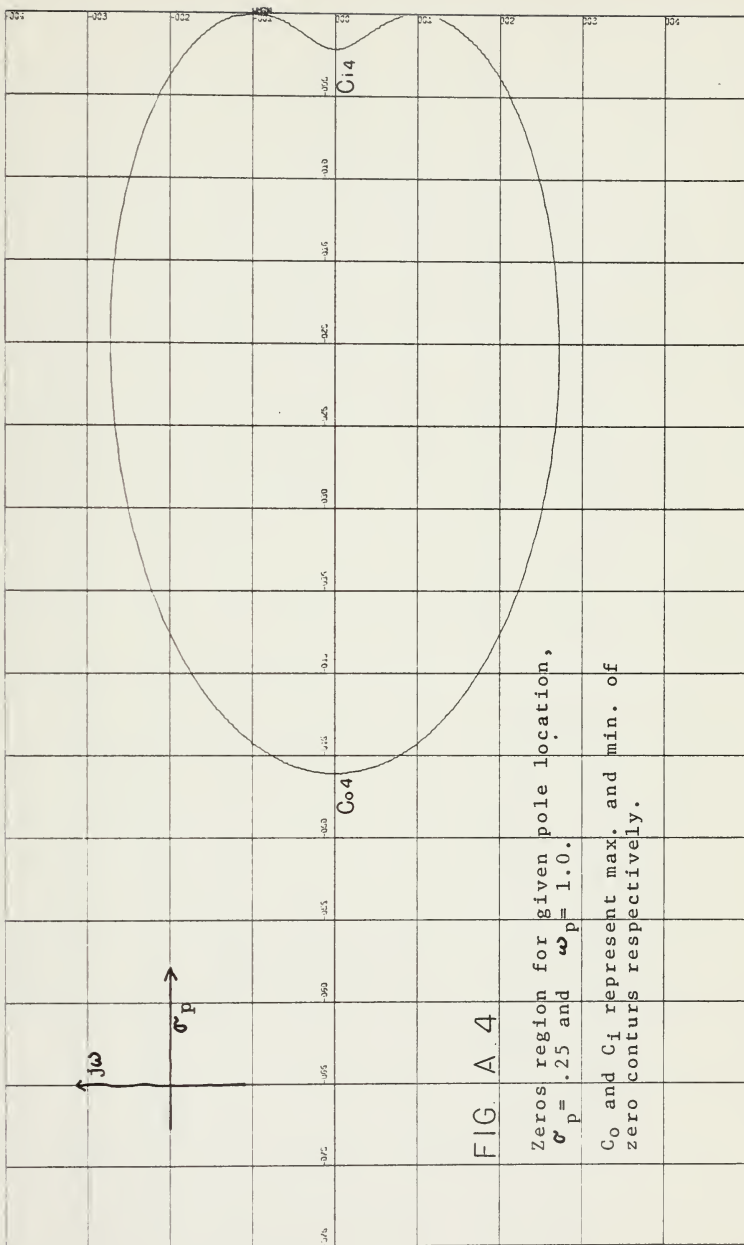
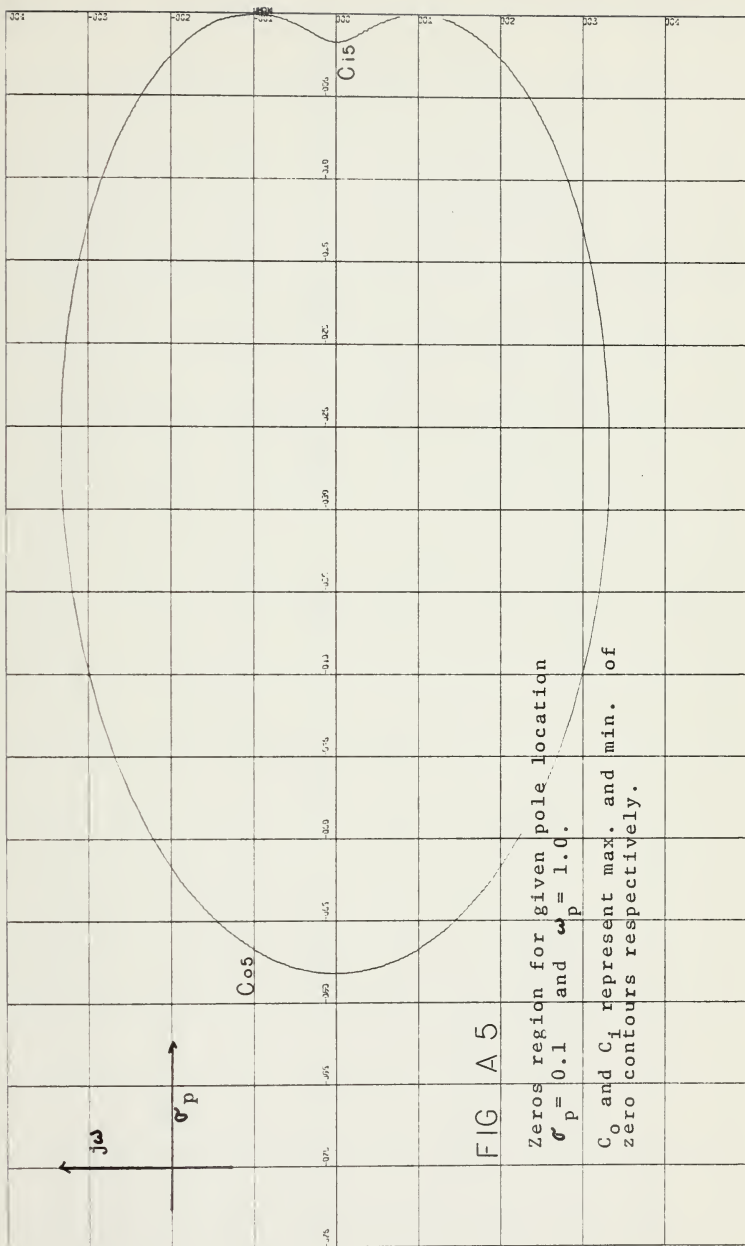


FIG A 4

Zeros region for given pole location,
 $\sigma_p = .25$ and $\omega_p = 1.0$.

C_0 and C_1 represent max. and min. of
 zero contours respectively.



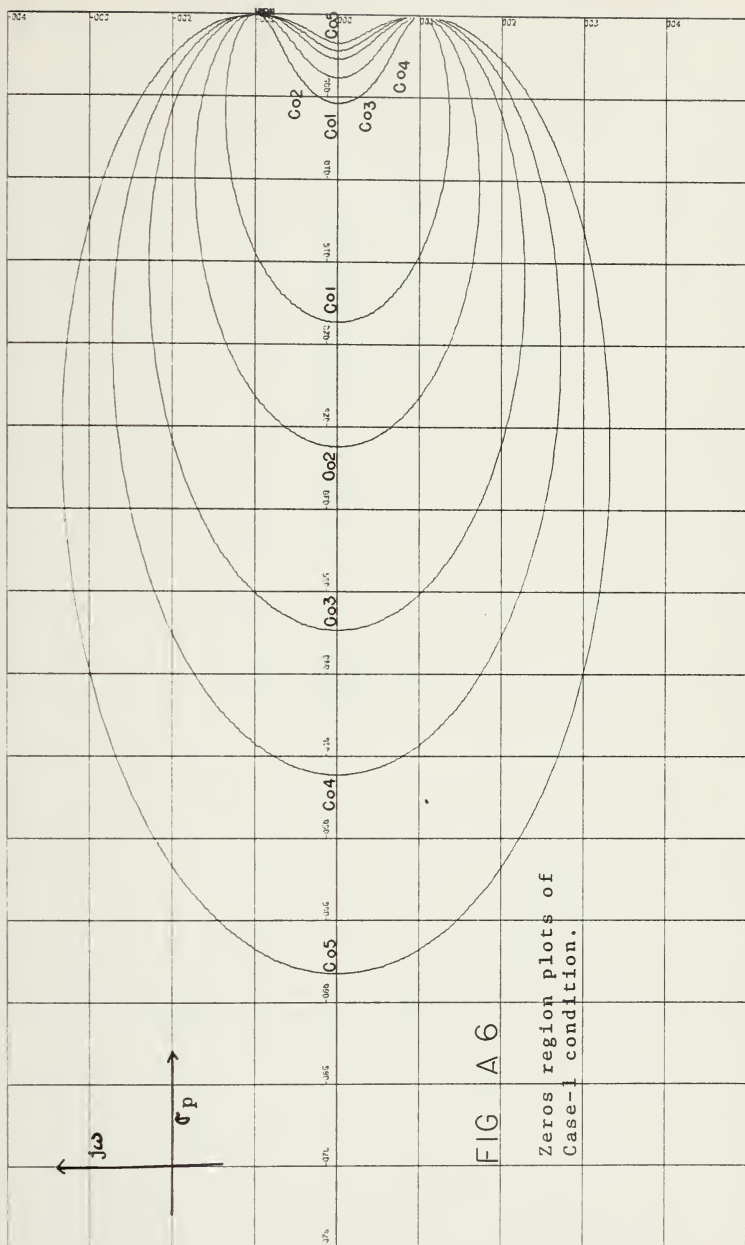


FIG A 6

Zeros region plots of
Case-1 condition.

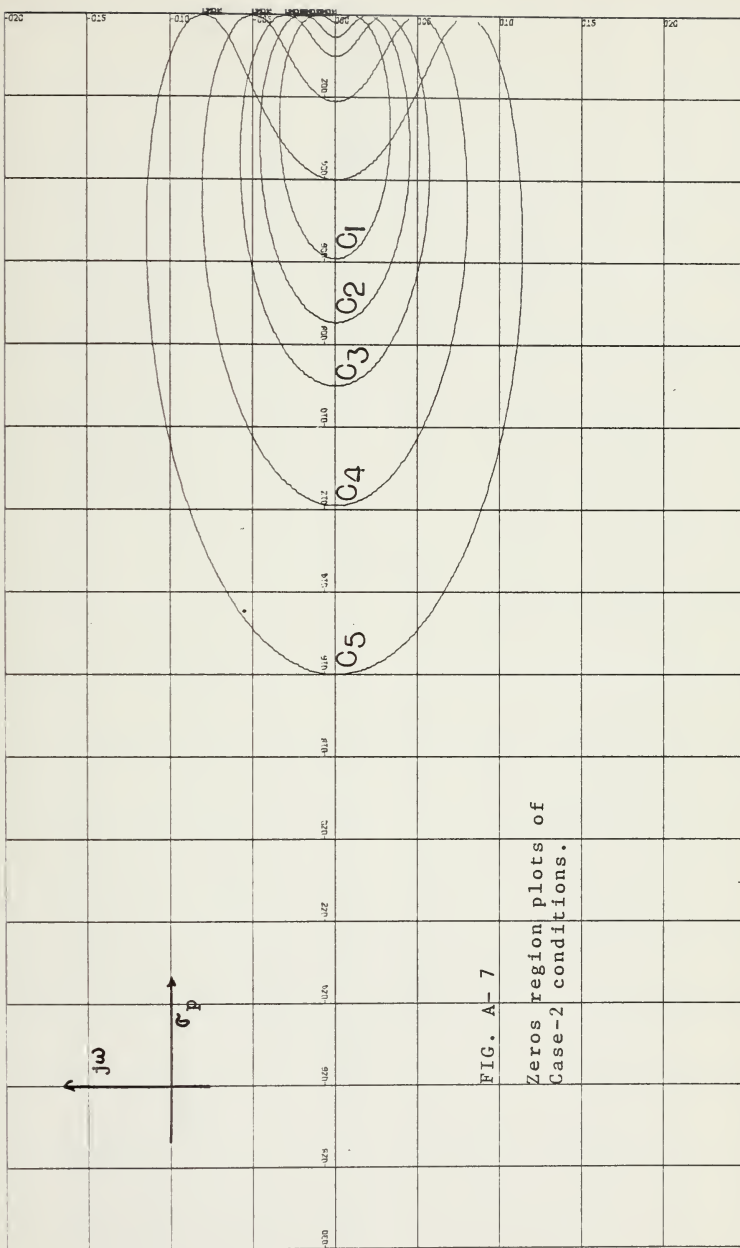


FIG. A-7

Zeros region plots of
Case-2 conditions.

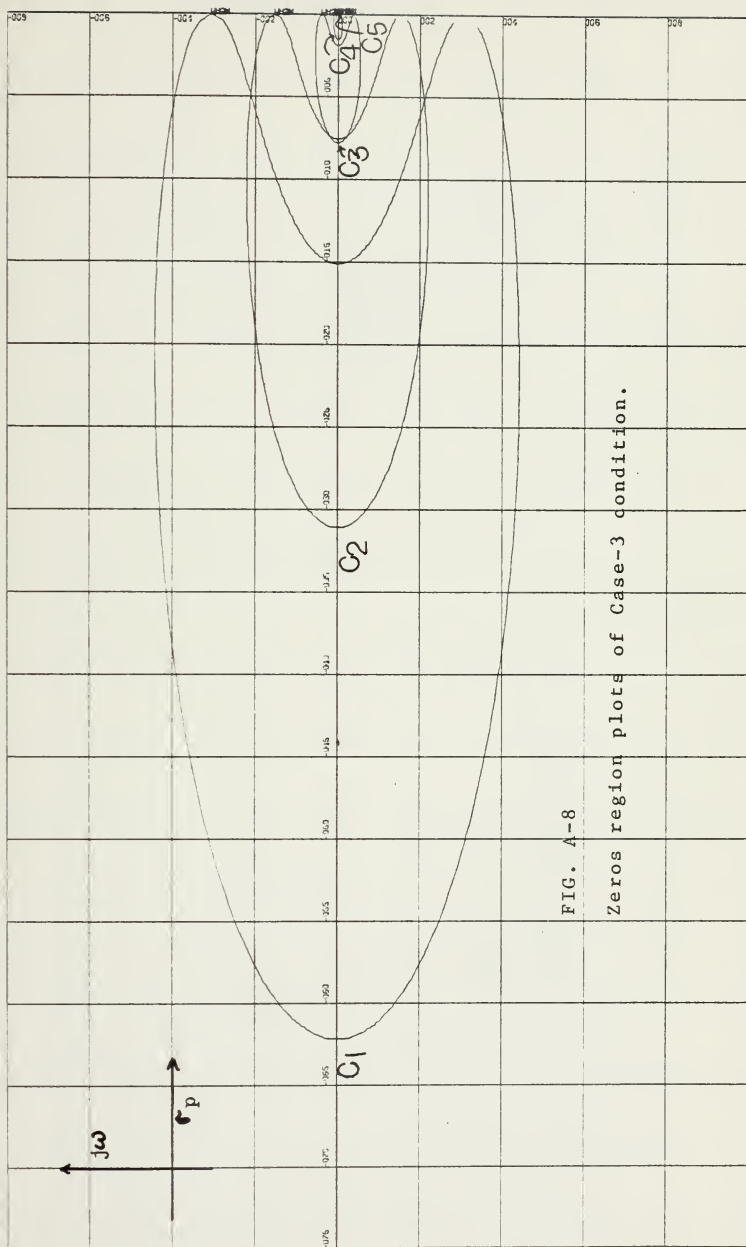
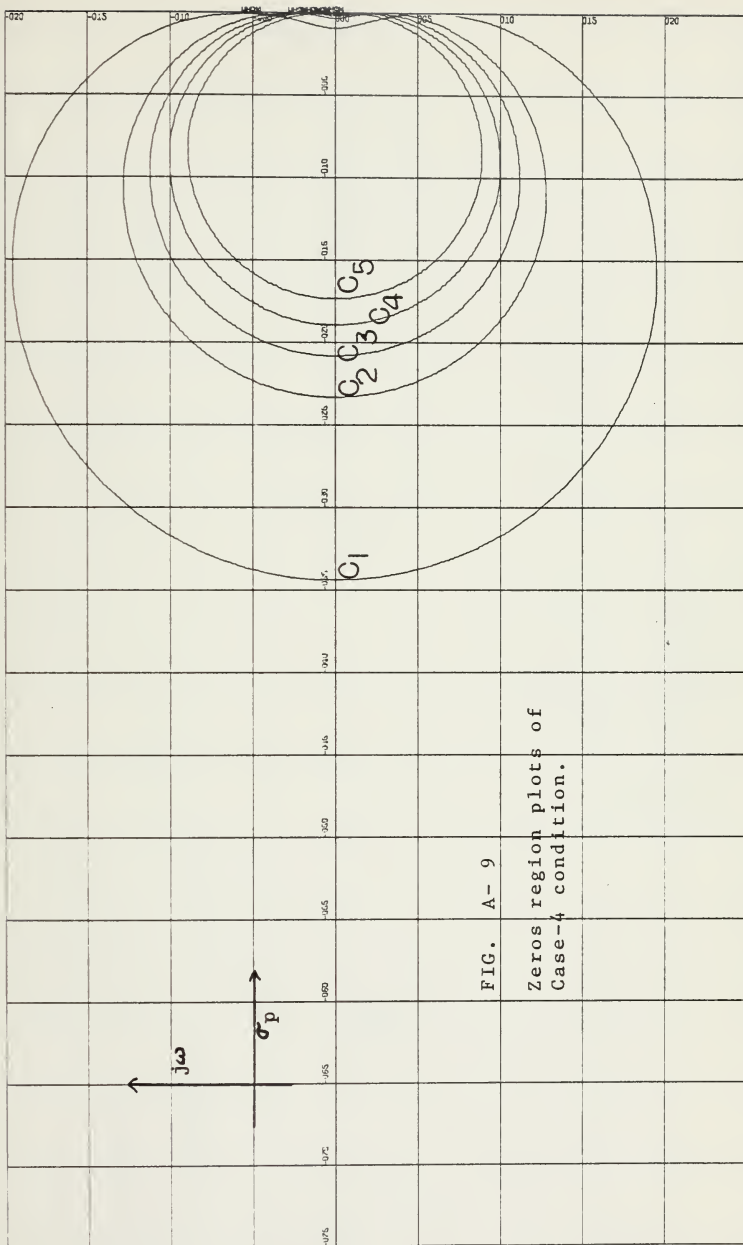


FIG. A-8

Zeros region plots of Case-3 condition.



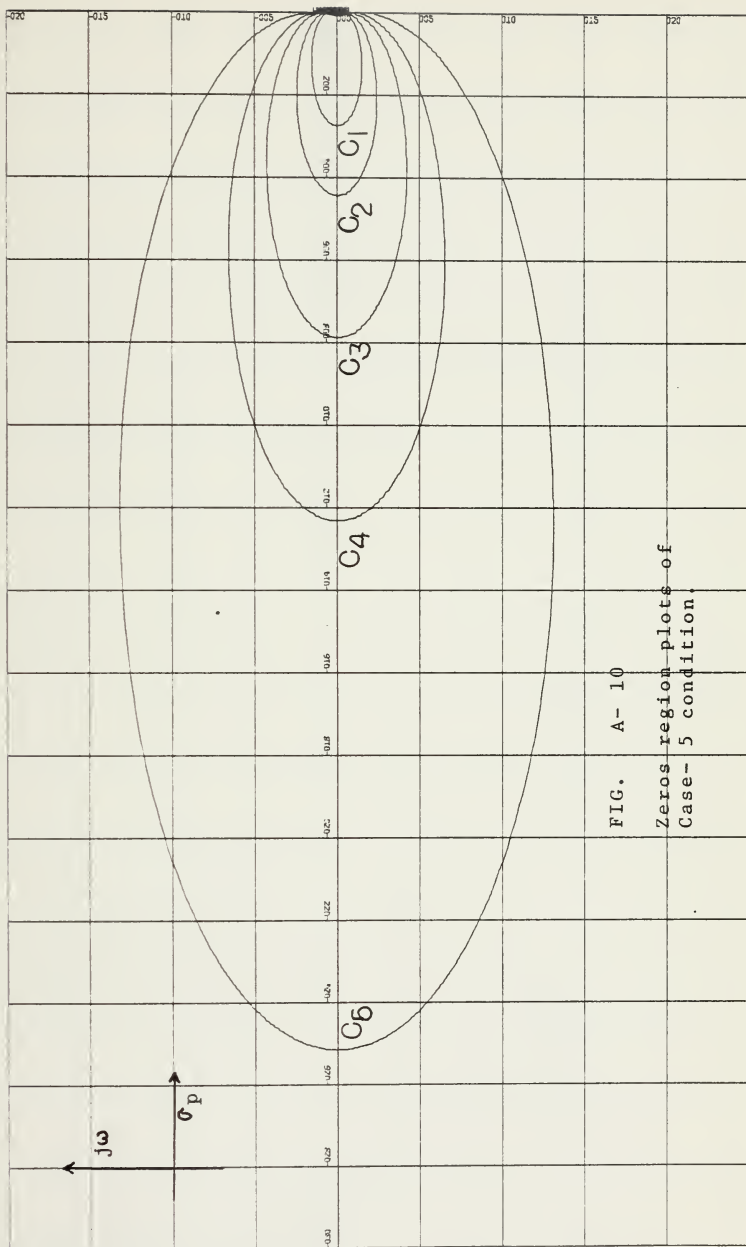


FIG. A-10
Zeros region plots of
Case-5 condition.

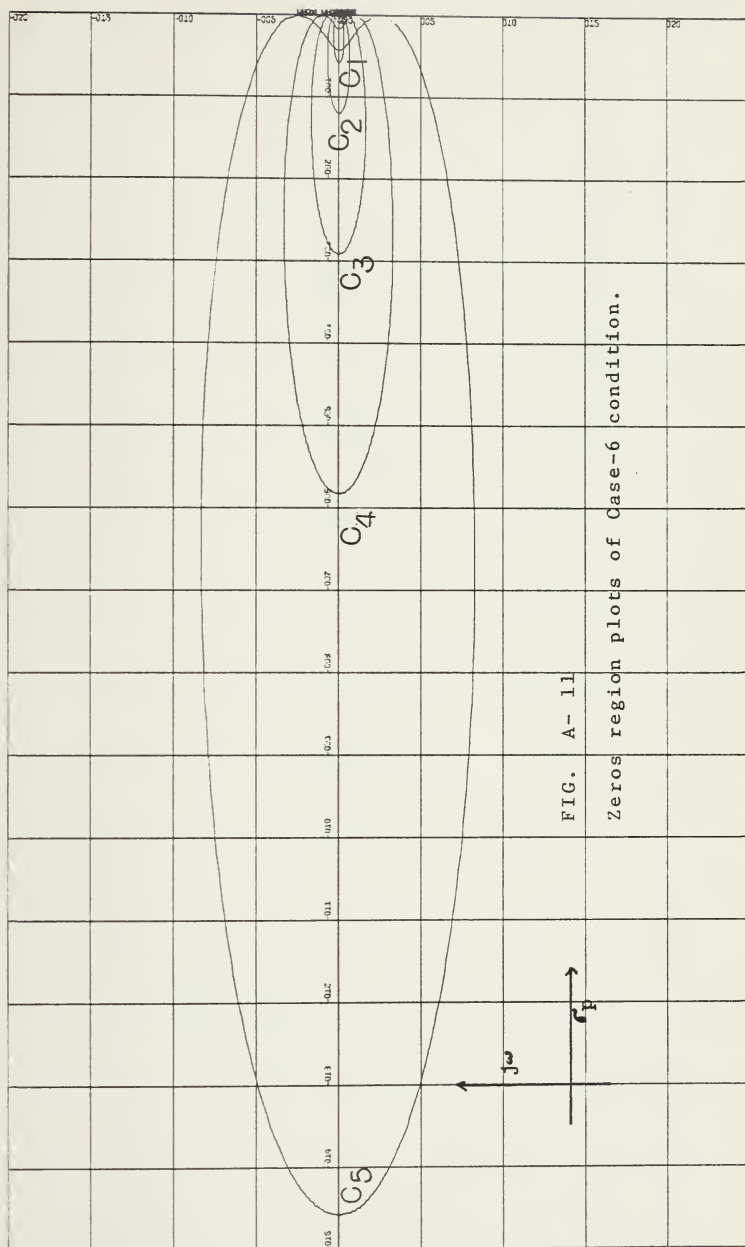


FIG. A-11

Zeros region plots of Case-6 condition.

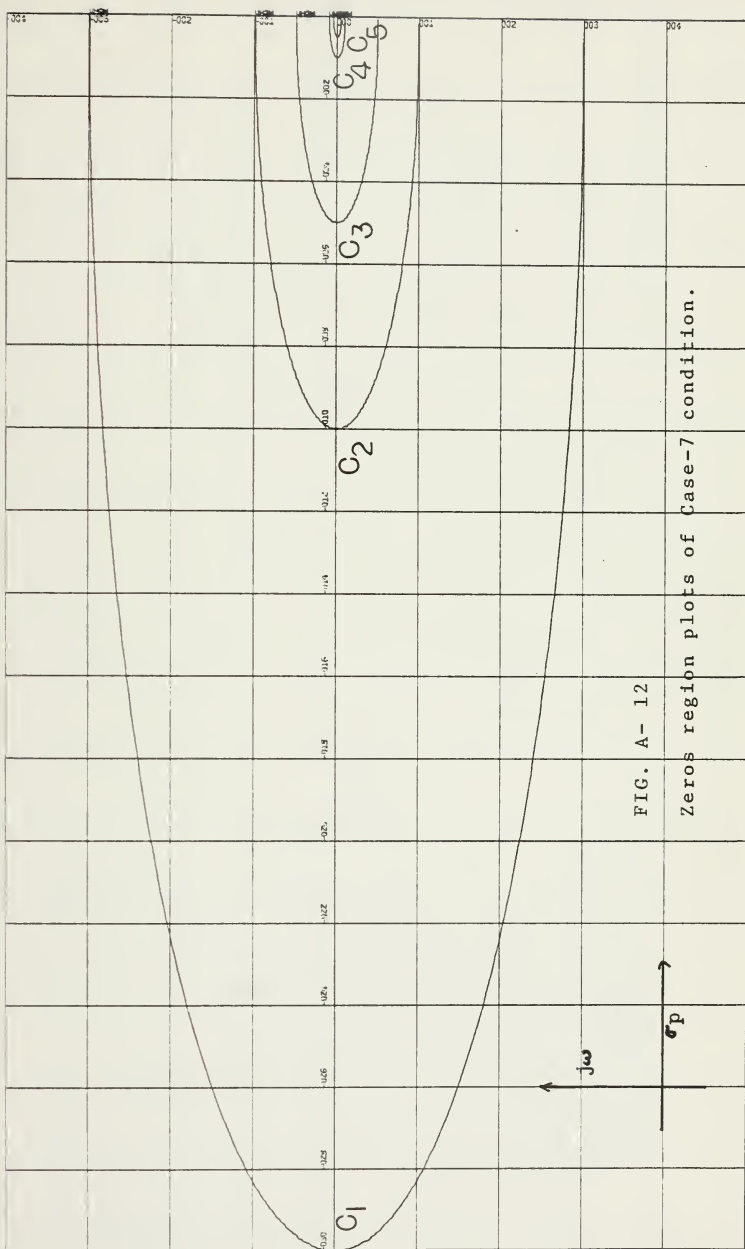


FIG. A-12

Zeros region plots of Case-7 condition.

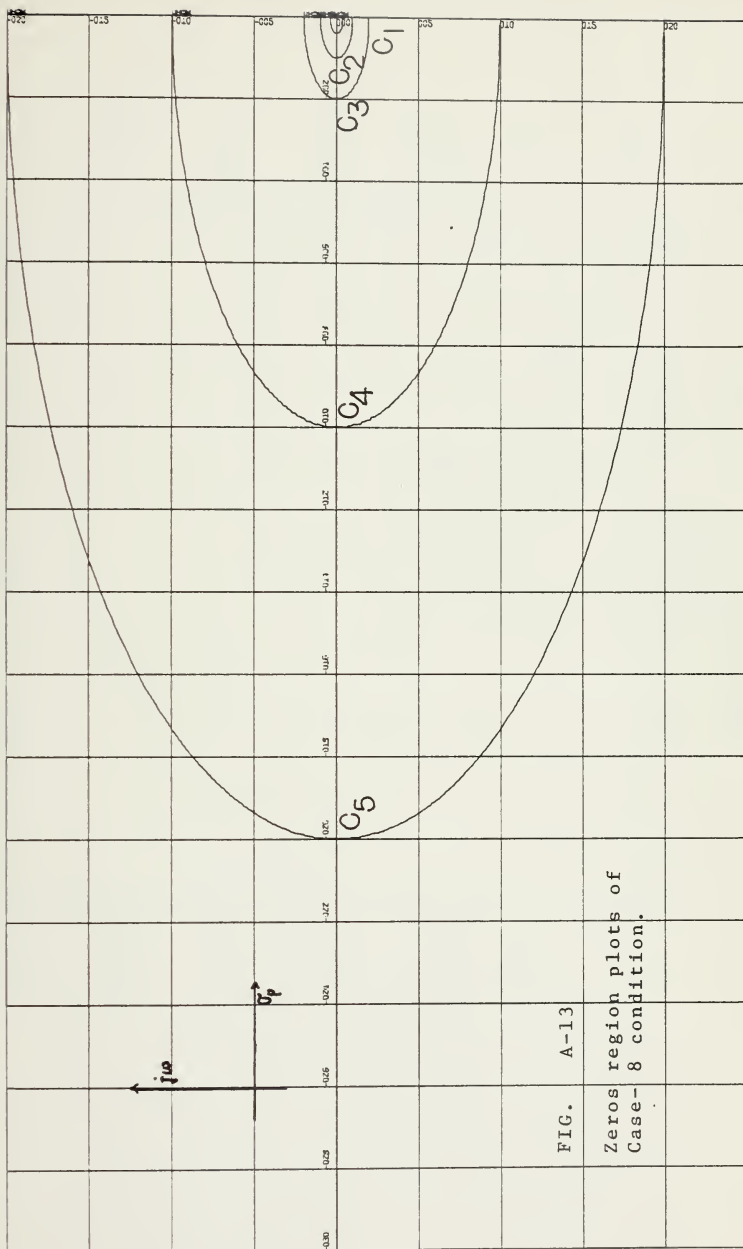


FIG. A-13

Zeros region plots of Case-8 condition.

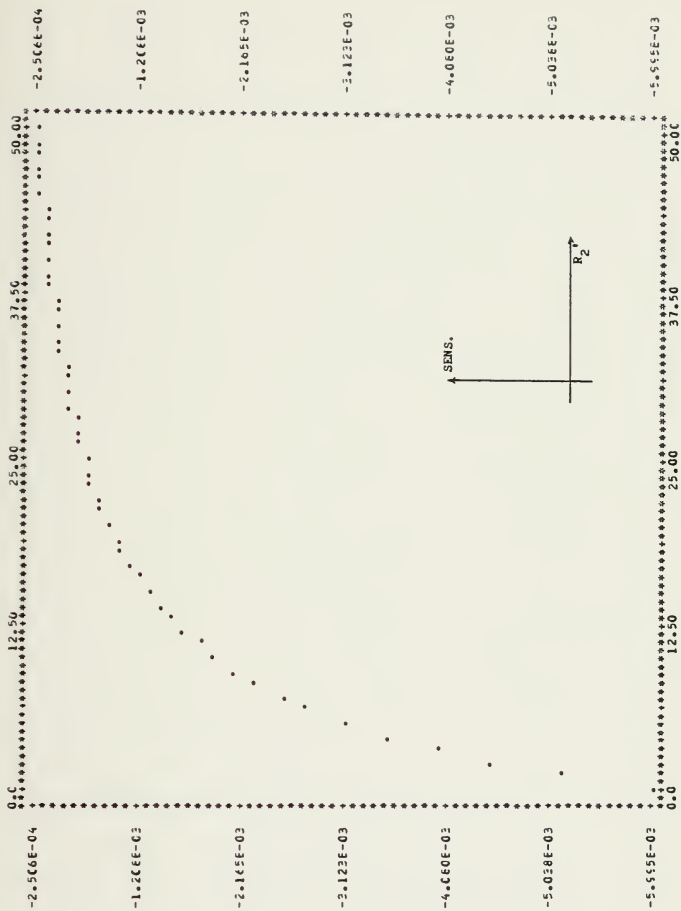


FIG B-1.

The plot of sensitivity vs R_2 , is shown for given frequency 1 r-1/sec.

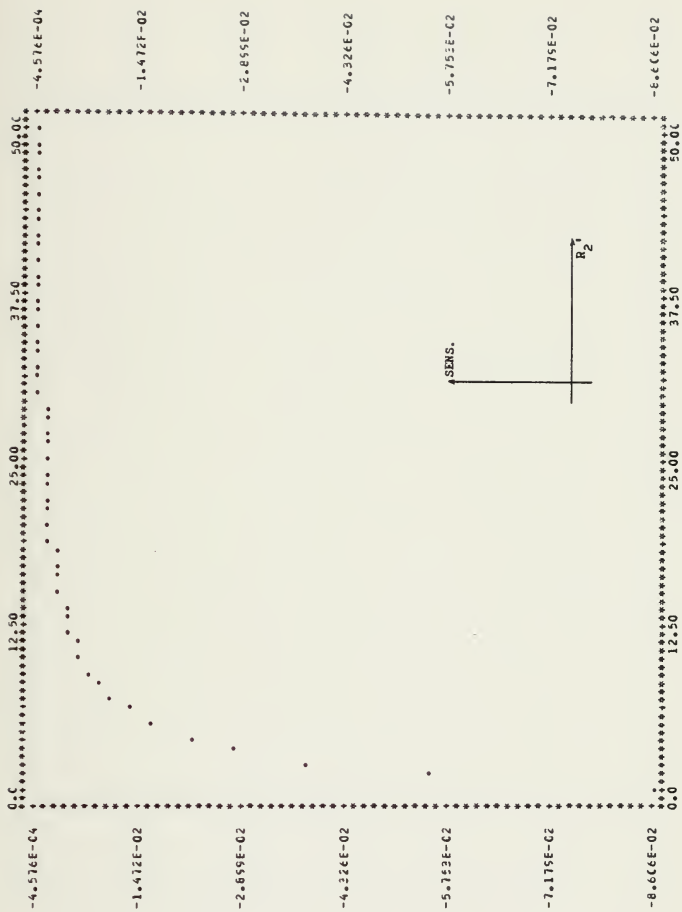


FIG. B 2.

Sensitivity plot vs R_2' is shown here for given
frequency 5 rad/sec.

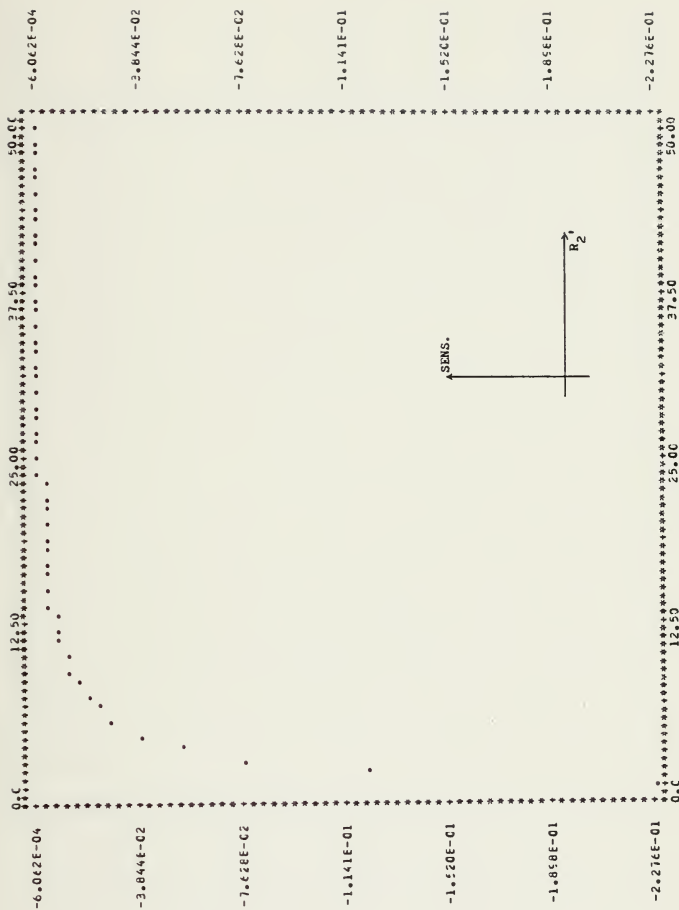


FIG. B 3.

The plot of sensitivity vs R_2 is shown here
for given frequency 10 rad/sec.

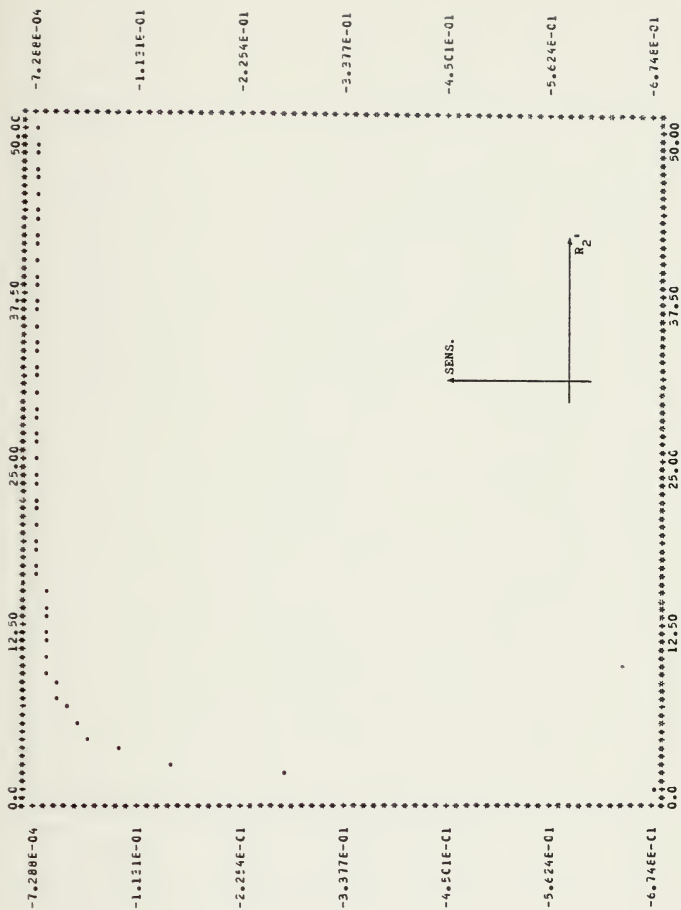


FIG. B4.

The plot of sensitivity vs R_2' is shown here for given frequency 50 rad/sec.

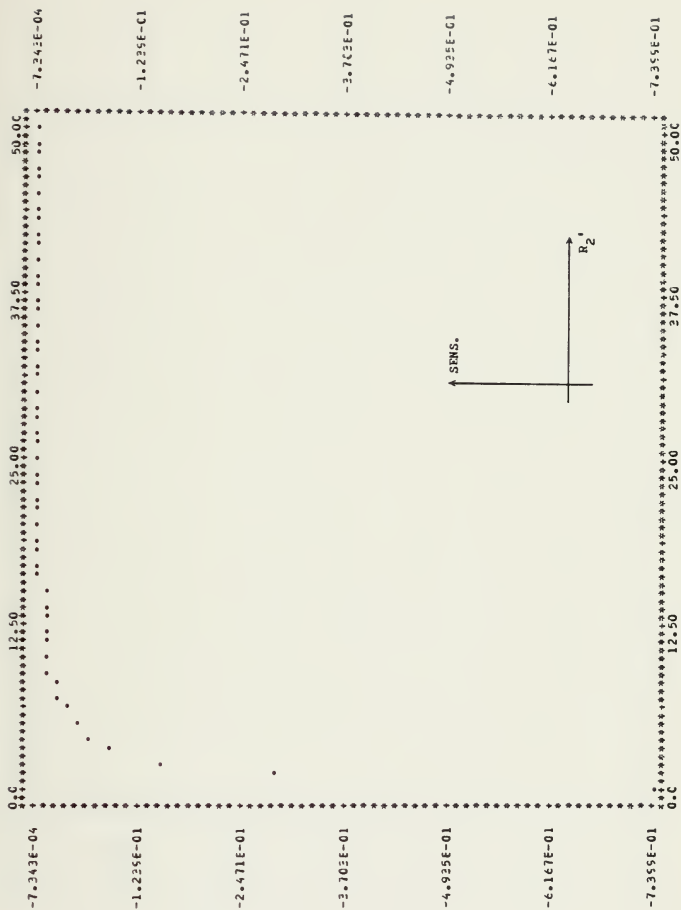


FIG. B 5.

The plot of sensitivity vs R_2 for given frequency
100 rad./sec.

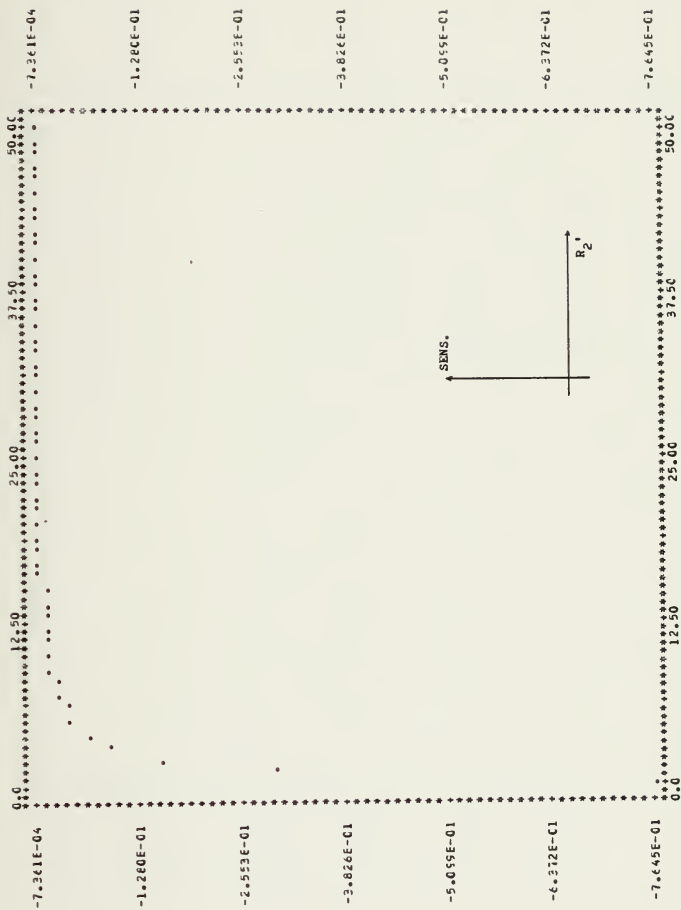


FIG. B 6.

The plot of sensitivity vs R_2' is shown here for
given frequency 500 rad/sec.

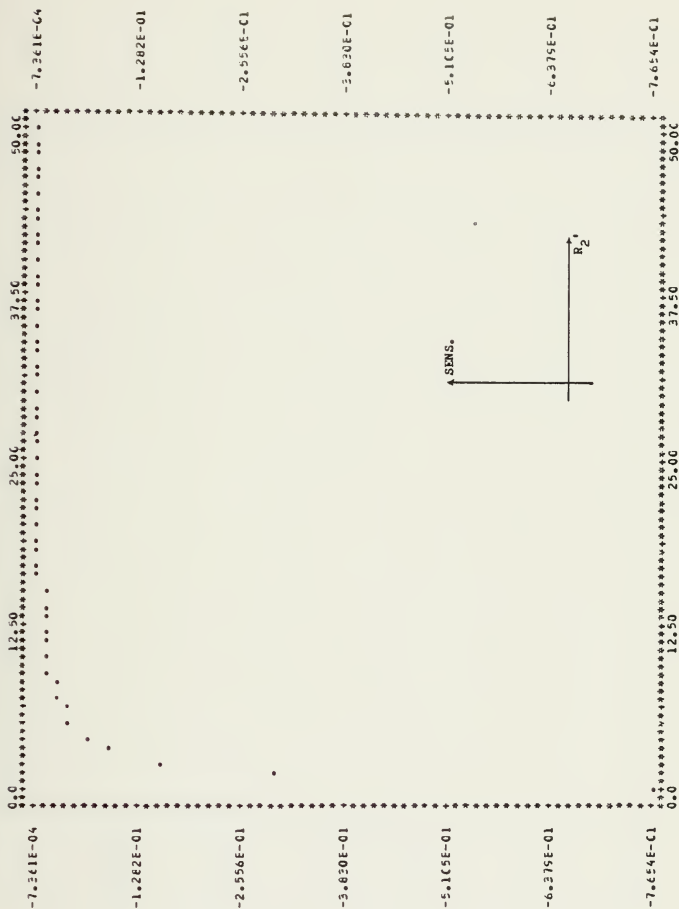


FIG. B 7.

The plot of sensitivity vs R_2 for given frequency 1000 rad/sec.

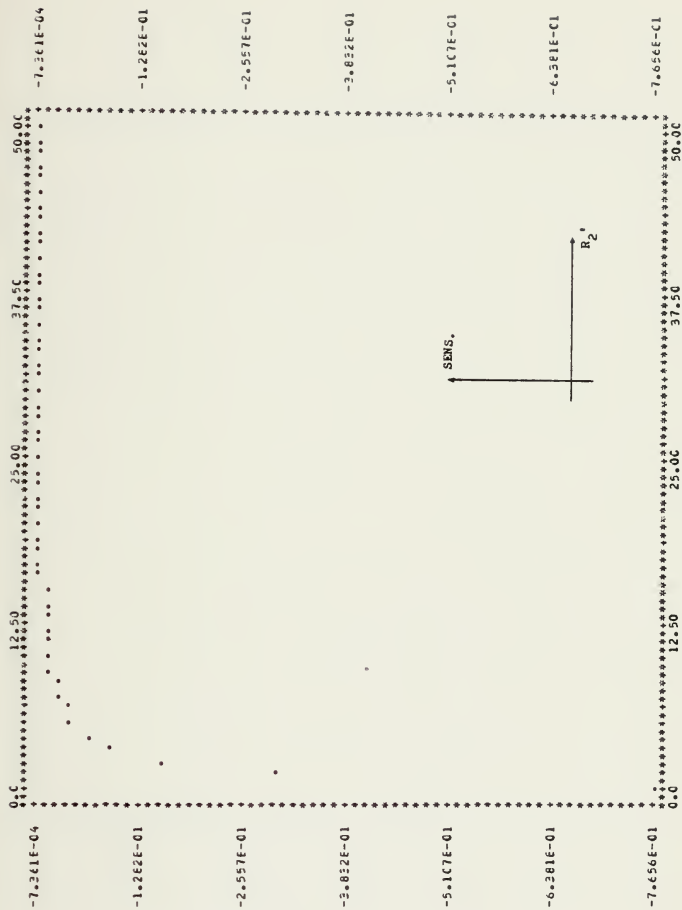


FIG. B 8.

The plot of sensitivity vs R_2 is shown for
given frequency 5000 rad/sec.

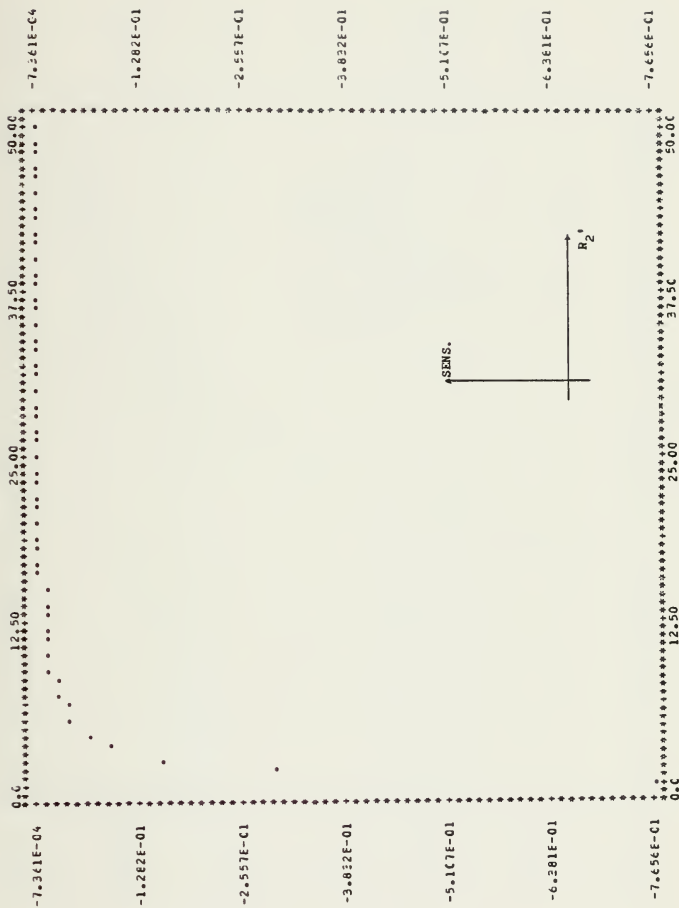


FIG. B 9

The plot of sensitivity vs R_2 for
given frequency 10000 rad/sec.

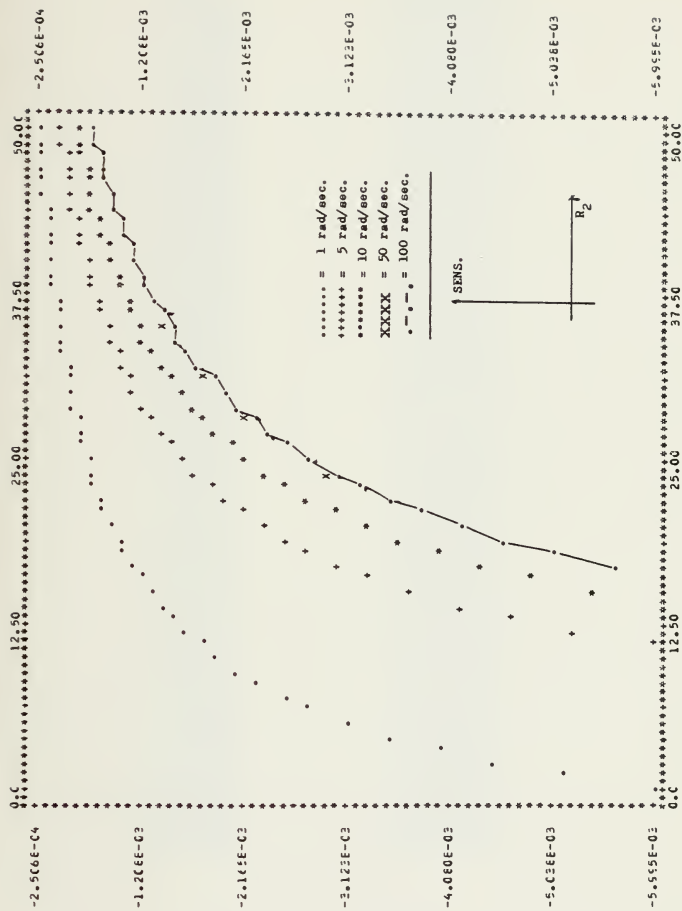


FIG. B.10.

The plots of sensitivity vs R_1 are shown here for given various frequencies.

THE VALUE OF SENSITIVITY AT GIVEN $w =$

1.000

| R2S | SENSITIVITY |
|--------|-------------|
| 0.0 | -0.005995 |
| 1.000 | -0.005160 |
| 2.000 | -0.004489 |
| 3.000 | -0.003940 |
| 4.000 | -0.003486 |
| 5.000 | -0.003107 |
| 6.000 | -0.002786 |
| 7.000 | -0.002512 |
| 8.000 | -0.002277 |
| 9.000 | -0.002073 |
| 10.000 | -0.001896 |
| 11.000 | -0.001740 |
| 12.000 | -0.001603 |
| 13.000 | -0.001481 |
| 14.000 | -0.001373 |
| 15.000 | -0.001276 |
| 16.000 | -0.001189 |
| 17.000 | -0.001111 |
| 18.000 | -0.001040 |
| 19.000 | -0.000976 |
| 20.000 | -0.000917 |
| 21.000 | -0.000864 |
| 22.000 | -0.000815 |
| 23.000 | -0.000770 |
| 24.000 | -0.000729 |
| 25.000 | -0.000691 |
| 26.000 | -0.000656 |
| 27.000 | -0.000623 |
| 28.000 | -0.000593 |
| 29.000 | -0.000565 |
| 30.000 | -0.000539 |
| 31.000 | -0.000515 |
| 32.000 | -0.000492 |
| 33.000 | -0.000471 |
| 34.000 | -0.000451 |
| 35.000 | -0.000432 |
| 36.000 | -0.000415 |
| 37.000 | -0.000398 |
| 38.000 | -0.000383 |
| 39.000 | -0.000368 |
| 40.000 | -0.000354 |
| 41.000 | -0.000341 |
| 42.000 | -0.000329 |
| 43.000 | -0.000317 |
| 44.000 | -0.000306 |
| 45.000 | -0.000296 |
| 46.000 | -0.000286 |
| 47.000 | -0.000276 |
| 48.000 | -0.000267 |
| 49.000 | -0.000259 |
| 50.000 | -0.000251 |

TABLE B - 1.

THE VALUE OF SENSITIVITY AT GIVEN W =

5.000

| RZS | SENSITIVITY |
|--------|-------------|
| 0.0000 | -0.086060 |
| 0.1000 | -0.0834744 |
| 0.2000 | -0.0803378 |
| 0.3000 | -0.0767736 |
| 0.4000 | -0.0728188 |
| 0.5000 | -0.0685711 |
| 0.6000 | -0.0640351 |
| 0.7000 | -0.0592115 |
| 0.8000 | -0.0541365 |
| 0.9000 | -0.0488722 |
| 1.0000 | -0.0434668 |
| 1.1000 | -0.0379799 |
| 1.2000 | -0.0325522 |
| 1.3000 | -0.0272445 |
| 1.4000 | -0.0220145 |
| 1.5000 | -0.0168371 |
| 1.6000 | -0.0117354 |
| 1.7000 | -0.0067041 |
| 1.8000 | -0.0017770 |
| 1.9000 | -0.0028334 |
| 2.0000 | -0.0002263 |
| 2.1000 | -0.0001981 |
| 2.2000 | -0.0001837 |
| 2.3000 | -0.0001707 |
| 2.4000 | -0.0001591 |
| 2.5000 | -0.0001487 |
| 2.6000 | -0.0001392 |
| 2.7000 | -0.0001306 |
| 2.8000 | -0.0001228 |
| 2.9000 | -0.0001157 |
| 3.0000 | -0.0001091 |
| 3.1000 | -0.0001031 |
| 3.2000 | -0.0000976 |
| 3.3000 | -0.0000925 |
| 3.4000 | -0.0000878 |
| 3.5000 | -0.0000835 |
| 3.6000 | -0.0000795 |
| 3.7000 | -0.0000757 |
| 3.8000 | -0.0000722 |
| 3.9000 | -0.0000690 |
| 4.0000 | -0.0000659 |
| 4.1000 | -0.0000631 |
| 4.2000 | -0.0000604 |
| 4.3000 | -0.0000579 |
| 4.4000 | -0.0000556 |
| 4.5000 | -0.0000534 |
| 4.6000 | -0.0000513 |
| 4.7000 | -0.0000494 |
| 4.8000 | -0.0000475 |
| 4.9000 | -0.0000458 |

TABLE B -2.

THE VALUE OF SENSITIVITY AT GIVEN W = 10.000

| R ² S | SENSITIVITY |
|------------------|-------------|
| 0.0000 | -0.227638 |
| 1.0000 | -0.123034 |
| 2.0000 | -0.076772 |
| 3.0000 | -0.052258 |
| 4.0000 | -0.037941 |
| 5.0000 | -0.028735 |
| 6.0000 | -0.022255 |
| 7.0000 | -0.018007 |
| 8.0000 | -0.014889 |
| 9.0000 | -0.012482 |
| 10.0000 | -0.010540 |
| 11.0000 | -0.009092 |
| 12.0000 | -0.007853 |
| 13.0000 | -0.006885 |
| 14.0000 | -0.006082 |
| 15.0000 | -0.005412 |
| 16.0000 | -0.004846 |
| 17.0000 | -0.004386 |
| 18.0000 | -0.004035 |
| 19.0000 | -0.003795 |
| 20.0000 | -0.003564 |
| 21.0000 | -0.003342 |
| 22.0000 | -0.003127 |
| 23.0000 | -0.002920 |
| 24.0000 | -0.002711 |
| 25.0000 | -0.002502 |
| 26.0000 | -0.002296 |
| 27.0000 | -0.002091 |
| 28.0000 | -0.001892 |
| 29.0000 | -0.001690 |
| 30.0000 | -0.001495 |
| 31.0000 | -0.001306 |
| 32.0000 | -0.001124 |
| 33.0000 | -0.000948 |
| 34.0000 | -0.000779 |
| 35.0000 | -0.000616 |
| 36.0000 | -0.000459 |
| 37.0000 | -0.000307 |
| 38.0000 | -0.000160 |
| 39.0000 | -0.000018 |
| 40.0000 | -0.000056 |
| 41.0000 | -0.000024 |
| 42.0000 | -0.000082 |
| 43.0000 | -0.000043 |
| 44.0000 | -0.000007 |
| 45.0000 | -0.000012 |
| 46.0000 | -0.000074 |
| 47.0000 | -0.000010 |
| 48.0000 | -0.000068 |
| 49.0000 | -0.000035 |
| 50.0000 | -0.000030 |
| 51.0000 | -0.000060 |

TABLE B - 3

THE VALUE OF SENSITIVITY AT GIVEN $W = 50.000$

| R^2S | SENSITIVITY |
|---------|-------------|
| C.C | -0.674758 |
| 1.0000 | -0.270416 |
| 2.0000 | -0.144071 |
| 3.0000 | -0.085186 |
| 4.0000 | -0.060166 |
| 5.0000 | -0.043783 |
| 6.0000 | -0.033117 |
| 7.0000 | -0.025519 |
| 8.0000 | -0.020636 |
| 9.0000 | -0.017112 |
| 10.0000 | -0.014305 |
| 11.0000 | -0.012135 |
| 12.0000 | -0.010423 |
| 13.0000 | -0.009065 |
| 14.0000 | -0.007900 |
| 15.0000 | -0.006970 |
| 16.0000 | -0.006233 |
| 17.0000 | -0.005587 |
| 18.0000 | -0.005033 |
| 19.0000 | -0.004557 |
| 20.0000 | -0.004146 |
| 21.0000 | -0.003788 |
| 22.0000 | -0.003475 |
| 23.0000 | -0.003195 |
| 24.0000 | -0.002954 |
| 25.0000 | -0.002737 |
| 26.0000 | -0.002542 |
| 27.0000 | -0.002368 |
| 28.0000 | -0.002211 |
| 29.0000 | -0.002066 |
| 30.0000 | -0.001931 |
| 31.0000 | -0.001804 |
| 32.0000 | -0.001687 |
| 33.0000 | -0.001579 |
| 34.0000 | -0.001477 |
| 35.0000 | -0.001371 |
| 36.0000 | -0.001271 |
| 37.0000 | -0.001176 |
| 38.0000 | -0.001089 |
| 39.0000 | -0.001009 |
| 40.0000 | -0.000933 |
| 41.0000 | -0.000861 |
| 42.0000 | -0.000793 |
| 43.0000 | -0.000729 |
| 44.0000 | -0.000669 |
| 45.0000 | -0.000613 |
| 46.0000 | -0.000560 |
| 47.0000 | -0.000511 |
| 48.0000 | -0.000465 |
| 49.0000 | -0.000422 |
| 50.0000 | -0.000382 |

TABLE B - 4

THE VALUE OF SENSITIVITY AT GIVEN W = 100.000

| R2S | SENSITIVITY |
|---------|-------------|
| 0.0 | -0.739854 |
| 1.0000 | -0.284703 |
| 2.0000 | -0.149352 |
| 3.0000 | -0.091353 |
| 4.0000 | -0.061453 |
| 5.0000 | -0.044653 |
| 6.0000 | -0.033354 |
| 7.0000 | -0.026652 |
| 8.0000 | -0.021151 |
| 9.0000 | -0.017155 |
| 10.0000 | -0.014456 |
| 11.0000 | -0.012259 |
| 12.0000 | -0.010653 |
| 13.0000 | -0.009551 |
| 14.0000 | -0.008953 |
| 15.0000 | -0.008056 |
| 16.0000 | -0.006654 |
| 17.0000 | -0.005555 |
| 18.0000 | -0.004854 |
| 19.0000 | -0.004453 |
| 20.0000 | -0.004157 |
| 21.0000 | -0.003855 |
| 22.0000 | -0.003558 |
| 23.0000 | -0.003359 |
| 24.0000 | -0.003251 |
| 25.0000 | -0.003152 |
| 26.0000 | -0.003053 |
| 27.0000 | -0.002955 |
| 28.0000 | -0.002856 |
| 29.0000 | -0.002757 |
| 30.0000 | -0.002657 |
| 31.0000 | -0.002557 |
| 32.0000 | -0.002459 |
| 33.0000 | -0.002351 |
| 34.0000 | -0.002253 |
| 35.0000 | -0.002154 |
| 36.0000 | -0.002056 |
| 37.0000 | -0.001957 |
| 38.0000 | -0.001859 |
| 39.0000 | -0.001751 |
| 40.0000 | -0.001653 |
| 41.0000 | -0.001554 |
| 42.0000 | -0.001456 |
| 43.0000 | -0.001358 |
| 44.0000 | -0.001259 |
| 45.0000 | -0.001161 |
| 46.0000 | -0.001063 |
| 47.0000 | -0.000964 |
| 48.0000 | -0.000866 |
| 49.0000 | -0.000768 |
| 50.0000 | -0.000670 |

TABLE B - 5

THE VALUE OF SENSITIVITY AT GIVEN W = 500.000

| R2S | SENSITIVITY |
|---------|-------------|
| 0.0000 | -0.764546 |
| 1.0000 | -0.2899726 |
| 2.0000 | -0.1511758 |
| 3.0000 | -0.092291 |
| 4.0000 | -0.062240 |
| 5.0000 | -0.0444933 |
| 6.0000 | -0.033355 |
| 7.0000 | -0.026655 |
| 8.0000 | -0.0217441 |
| 9.0000 | -0.017441 |
| 10.0000 | -0.014433 |
| 11.0000 | -0.0122444 |
| 12.0000 | -0.0106995 |
| 13.0000 | -0.0093933 |
| 14.0000 | -0.0080533 |
| 15.0000 | -0.007112 |
| 16.0000 | -0.00627 |
| 17.0000 | -0.00555 |
| 18.0000 | -0.004901 |
| 19.0000 | -0.00438 |
| 20.0000 | -0.003900 |
| 21.0000 | -0.00347 |
| 22.0000 | -0.003095 |
| 23.0000 | -0.00278 |
| 24.0000 | -0.002500 |
| 25.0000 | -0.00225 |
| 26.0000 | -0.002033 |
| 27.0000 | -0.00186 |
| 28.0000 | -0.0017 |
| 29.0000 | -0.001533 |
| 30.0000 | -0.001364 |
| 31.0000 | -0.001236 |
| 32.0000 | -0.001167 |
| 33.0000 | -0.0011 |
| 34.0000 | -0.001046 |
| 35.0000 | -0.001033 |
| 36.0000 | -0.001066 |
| 37.0000 | -0.001055 |
| 38.0000 | -0.001000 |
| 39.0000 | -0.001019 |
| 40.0000 | -0.001032 |
| 41.0000 | -0.001080 |
| 42.0000 | -0.001031 |
| 43.0000 | -0.001055 |
| 44.0000 | -0.001042 |
| 45.0000 | -0.001022 |
| 46.0000 | -0.001055 |
| 47.0000 | -0.001000 |
| 48.0000 | -0.0010797 |
| 49.0000 | -0.001065 |
| 50.0000 | -0.0010726 |

TABLE B - 6

THE VALUE OF SENSITIVITY AT GIVEN W = 1000.000

| R2S | SENSITIVITY |
|--------|-------------|
| 0.0 | -0.765334 |
| 1.000 | -0.289687 |
| 2.000 | -0.151215 |
| 3.000 | -0.092615 |
| 4.000 | -0.062245 |
| 5.000 | -0.044592 |
| 6.000 | -0.033331 |
| 7.000 | -0.026499 |
| 8.000 | -0.021266 |
| 9.000 | -0.017443 |
| 10.000 | -0.014565 |
| 11.000 | -0.012343 |
| 12.000 | -0.010651 |
| 13.000 | -0.009519 |
| 14.000 | -0.008600 |
| 15.000 | -0.007711 |
| 16.000 | -0.006932 |
| 17.000 | -0.006265 |
| 18.000 | -0.005610 |
| 19.000 | -0.005046 |
| 20.000 | -0.004530 |
| 21.000 | -0.004067 |
| 22.000 | -0.003651 |
| 23.000 | -0.003279 |
| 24.000 | -0.002941 |
| 25.000 | -0.002637 |
| 26.000 | -0.002363 |
| 27.000 | -0.002123 |
| 28.000 | -0.001917 |
| 29.000 | -0.001734 |
| 30.000 | -0.001573 |
| 31.000 | -0.001434 |
| 32.000 | -0.001316 |
| 33.000 | -0.001217 |
| 34.000 | -0.001136 |
| 35.000 | -0.001071 |
| 36.000 | -0.001020 |
| 37.000 | -0.000981 |
| 38.000 | -0.000950 |
| 39.000 | -0.000927 |
| 40.000 | -0.000910 |
| 41.000 | -0.000899 |
| 42.000 | -0.000893 |
| 43.000 | -0.000891 |
| 44.000 | -0.000893 |
| 45.000 | -0.000899 |
| 46.000 | -0.000908 |
| 47.000 | -0.000920 |
| 48.000 | -0.000937 |
| 49.000 | -0.000957 |
| 50.000 | -0.000973 |

TABLE B - 7

THE VALUE OF SENSITIVITY AT GIVEN W = 5000.000

| R2S | SENSITIVITY |
|--------|-------------|
| 0.0000 | -0.765613 |
| 0.0000 | -0.289959 |
| 0.0000 | -0.151234 |
| 0.0000 | -0.092627 |
| 0.0000 | -0.062500 |
| 0.0000 | -0.044595 |
| 0.0000 | -0.033933 |
| 0.0000 | -0.026501 |
| 0.0000 | -0.021267 |
| 0.0000 | -0.017444 |
| 0.0000 | -0.014566 |
| 0.0000 | -0.012246 |
| 0.0000 | -0.010597 |
| 0.0000 | -0.009555 |
| 0.0000 | -0.008054 |
| 0.0000 | -0.007113 |
| 0.0000 | -0.006327 |
| 0.0000 | -0.005665 |
| 0.0000 | -0.005102 |
| 0.0000 | -0.004619 |
| 0.0000 | -0.004201 |
| 0.0000 | -0.003837 |
| 0.0000 | -0.003515 |
| 0.0000 | -0.003239 |
| 0.0000 | -0.002991 |
| 0.0000 | -0.002770 |
| 0.0000 | -0.002573 |
| 0.0000 | -0.002396 |
| 0.0000 | -0.002237 |
| 0.0000 | -0.002093 |
| 0.0000 | -0.001963 |
| 0.0000 | -0.001844 |
| 0.0000 | -0.001736 |
| 0.0000 | -0.001637 |
| 0.0000 | -0.001547 |
| 0.0000 | -0.001463 |
| 0.0000 | -0.001386 |
| 0.0000 | -0.001315 |
| 0.0000 | -0.001250 |
| 0.0000 | -0.001189 |
| 0.0000 | -0.001133 |
| 0.0000 | -0.001080 |
| 0.0000 | -0.001031 |
| 0.0000 | -0.000985 |
| 0.0000 | -0.000943 |
| 0.0000 | -0.000903 |
| 0.0000 | -0.000865 |
| 0.0000 | -0.000830 |
| 0.0000 | -0.000797 |
| 0.0000 | -0.000766 |
| 0.0000 | -0.000736 |

TABLE B - 8

THE VALUE OF SENSITIVITY AT GIVEN $W = 10000.000$

| R2S | SENSITIVITY |
|---------|-------------|
| 0.0 | -0.765621 |
| 1.000 | -0.289540 |
| 2.0000 | -0.151234 |
| 3.0000 | -0.092334 |
| 4.0000 | -0.062500 |
| 5.0000 | -0.044595 |
| 6.0000 | -0.033333 |
| 7.0000 | -0.026501 |
| 8.0000 | -0.021267 |
| 9.0000 | -0.017444 |
| 10.0000 | -0.014566 |
| 11.0000 | -0.012346 |
| 12.0000 | -0.010637 |
| 13.0000 | -0.009195 |
| 14.0000 | -0.008054 |
| 15.0000 | -0.007113 |
| 16.0000 | -0.006327 |
| 17.0000 | -0.005665 |
| 18.0000 | -0.005102 |
| 19.0000 | -0.004619 |
| 20.0000 | -0.004201 |
| 21.0000 | -0.003857 |
| 22.0000 | -0.003551 |
| 23.0000 | -0.003299 |
| 24.0000 | -0.003091 |
| 25.0000 | -0.002927 |
| 26.0000 | -0.002773 |
| 27.0000 | -0.002639 |
| 28.0000 | -0.002517 |
| 29.0000 | -0.002403 |
| 30.0000 | -0.002294 |
| 31.0000 | -0.002194 |
| 32.0000 | -0.002103 |
| 33.0000 | -0.002016 |
| 34.0000 | -0.001937 |
| 35.0000 | -0.001863 |
| 36.0000 | -0.001796 |
| 37.0000 | -0.001733 |
| 38.0000 | -0.001674 |
| 39.0000 | -0.001619 |
| 40.0000 | -0.001568 |
| 41.0000 | -0.001520 |
| 42.0000 | -0.001475 |
| 43.0000 | -0.001433 |
| 44.0000 | -0.001393 |
| 45.0000 | -0.001355 |
| 46.0000 | -0.001319 |
| 47.0000 | -0.001285 |
| 48.0000 | -0.001253 |
| 49.0000 | -0.001223 |
| 50.0000 | -0.001194 |

TABLE B - 9

APPENDIX B
COMPUTER PROGRAM

A. ZEROS REGION

This program will plot the realizability region of general bi-quadratic function of the form

$$Z(s) = \frac{s^2 + 2*\text{SIGMAZ}*s + \text{OMEGAZ}^2}{s^2 + 2*\text{SIGMAP}*s + \text{OMEGAP}^2}$$

The input to this program is via punched card. One card is required for each plot. The input variables are Sigmap and Omegap specified in columns 1 - 20 as two fields of F 10.3 format.

The output is a plot of allowable region for zeros of Z(s) for a given pair of poles. The criterion for the plot is that Z(s) must be positive real.

The output may be either one (or both) of two types of plots depending on the needs of the programmers. If a fast solution is desired the "CALL DRAW" statements must be removed to enable the program to be run on QUICKRUN. The result will be a rough plot on the line printer output.

If maximum accuracy is desired a CALCOMP plot may be obtained by making a regular FORTCLG run with the "CALL DRAW" cards in the deck. In this case a line printer plot will also be generated, unless the "CALL PLOTP" cards are moved. For the CALCOMP run, "REGION.GO-100K" must be specified on the EXEC card.

The routines DRAW and PLOTP are called by this program. Both are in the MPSLIB at NPS. Neither a copy of the decks nor special job control language is needed to run this program on the NPS IBM 360.

The computer program is shown in Figure A-14.

B. SENSITIVITY FUNCTION

This program will plot the sensitivity of general biquadratic function with respect to the changing of its components at a particular frequency.

The equation used in this program is,

$$S_{R_2}^{T(j\omega, R_2')} (j\omega, R_2') = - \frac{W (T(j\omega, R_2' = 0) - T(j\omega, R_2' = \text{INF.}))}{(W + R_2')^2}$$

where $T(j\omega, R_2')$, W , $T(j\omega, R_2' = 0)$, $T(j\omega, R_2' = \text{INF.})$ and R_2' correspond to Figure 17 in Chapter IV. E.

The output is a plot of the magnitude of the sensitivity function above versus R_2' .

The input of this program is via punched card. One card is required for each plot. The input variable is frequency in rad/sec. specified in columns 1 - 10 as one field of F 10.3 format.

The output is a rough plot on line printer output.

The routine "CALL PLOTP" is called by this program.

The computer program is shown in Figure B-11.

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